POTENTIAL OF COAL STRIP-MINE SPOILS AS AQUIFERS IN THE POWDER RIVER BASIN

THE OLD WEST REGIONAL COMMISSION
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Project Completion Report

POTENTIAL OF COAL STRIP-MINE SPOILS AS AQUIFERS IN THE POWDER RIVER BASIN

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FOREWORD

This project was designed to help furnish guidelines for determining the potential of strip-mining fills as underground aquifers and water storage areas in the Powder River basin. The Commission is indebted to all who participated in collection of the information and preparation of the report.

Warren C. Wood

Warren C. Wood

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ABSTRACT

The Powder River Basin contains some of the largest coal deposits in the world. Despite the immense coal production that will undoubtedly occur in this area in the next few decades, little is known about the hydrology of the spoils that occur as a byproduct of strip mine operations.

The Tongue River Formation of the Paleocene Fort Union Group contains most of the strippable coal deposits in the Powder River Basin. Flat lying low sulfur coal beds up to 200 ft. thick are typically overlain by semiconsolidated shale and sandstone. Typical overburden to coal thickness ratios in working mines are 2:1. The overburden is generally dragline or scraper-dumped into the excavated pit.

Pump tests were conducted to determine the aquifer characteristics of the mine spoils of two coal strip mines in western Sheridan County, Wyoming. The results of the pump tests show an average permeability of 450 gpd/ft^2 and an average storage coefficient of 0.170 for the Hidden Water Creek mine where dragline-emplaced spoils occur, and an average of 4 gpd/ft^2 permeability and 0.233 storage coefficient for the Bighorn coal mine where scraper and bulldozer-emplaced spoils occur.

Six coal strip mines were studied using field infiltration and laboratory permeability apparatus to determine hydrologic characteristics. Data from 44 sites indicate that the permeability is primarily related to density, which in turn is due to method of emplacement and composition. Spoils emplaced by dragline show higher laboratory permeability than those emplaced by scraper or truck. This is presumably due to greater compaction caused by machinery moving over the surface of the spoils. Local stratigraphy, however, has a great influence on the hydrologic

characteristics of the spoils. Areas with large amounts of alluvium or sandstone in the overburden show significantly larger values of laboratory permeability than those where overburden consists chiefly of siltstone or shale.

Chemical analyses of 32 water samples show a significant difference of the quality of ground water in spoils compared to natural ground water from wells in the Tongue River Formation. Water in spoils contains greater sulfate, calcium, magnesium, and total dissolved solids. The solution of gypsum and oxidation of pyrite is believed to contribute to the high mineral content of spoils water. However, the mineral content of natural ground water is also sufficably high to limit its usefulness.

The possibility of utilizing the abandoned spoils as ground water storage areas is feasible due to the moderately high permeability. However, the poor quality of the ground water that would be pumped out of the spoils would appear to limit its usefulness.

INTRODUCTION

The production of coal from the western United States is certain to play an important role as the need for energy increases. According to Flint and Skinner (1974), 18% of the energy consumed in the United States in 1972 came from coal. Coal in the western United States is low in sulfur, and is superior in this respect to the mid-western or Appalachian coals. According to the U.S. Geological Survey (1973), the total production of western coal in 1972 was about 40 million tons, but may increase to over 200 million tons per year by the year 2000. This would involve an increase in the area of stripped land from 33 square miles disturbed as of 1972 to 300 square miles by the year 2000. According to Hubert (1976) coal mining throughout the world may not peak until a century or two from now.

On July 1, 1974, the Old West Regional Commission funded a two year project to South Dakota School of Mines and Technology to study the permeability and porosity of coal strip-mine fills in the Powder River Basin, and to determine if these deposits could be used as future ground water storage areas. This report summarizes the research conducted under this grant.

The Powder River Basin includes the area roughly 100 miles wide and 200 miles long between the Bighorn Mountains and the Black Hills. The rocks underlying the Powder River Basin are generally semi-consolidated sediments of Tertiary age, and contain some of the largest known low-sulfur, subbituminous coal beds anywhere in the world (USBM, 1971; Murray, 1976). These coal beds have been mined sporadically in the past. Underground mining was done after World War II, but was marginal economically, and was hampered by accidents such as the disasterous explosion at Bear Creek, Montana. With the advent of large earth-moving

machines in the past three decades, it became feasible to mine these coal beds in large open pits. There are presently about ten major open pit mines in the Powder River Basin (Keefer, 1974). Some of these pits are so large that they can be seen from space. Figure 1 is a space photograph of the western Powder River showing the major coal mines studied in the project. The white areas near Colstrip and Decker, Montana, are disturbed ground caused by the large open pit coal mines.

The Old West Regional States are facing development of their natural resources, particularly coal and water, on a scale and at a rate not contemplated heretofore. Large amounts of coal and water have been or are being allocated for coal conversion to gas, and plans for mining and plant construction are under discussion in many of these States. Recent federal and state legislation has had a number of effects, including that of making the citizens of the several States involved aware of the very large gap existing between the problems posed by resources development and the body of research that has been accomplished to date.

Because mining activities are in full operation currently within the Old West Region it is essential that knowledge of the chemical and physical properties of the land also progresses so that the most beneficial and advanced methods can be used in reclamation of mined lands. Not only has the restoration of mined lands to near a natural state become an important consideration but future land use as well is intertwined in the process of reclamation.

Extensive research has been conducted on plants and the rehabilitation problems of strip mines in the arid west (Packer, 1975). A recent publication by the U.S. Bureau of Mines, (Persse, 1975), includes references to articles on this subject. Coal strip-mine spoil revegetation studies have been carried out by the Montana Agricultural Station

(e.g. Hodder, 1974), the U.S. Forest Service (Packer, 1974), and other agencies.

One part of the environment which is an important variable in the rehabilitation of the mined areas is water. Water is exceptionally precious in the Old West Region States and as such holds the key to most economic, recreational, and reclamation developments. The average annual precipitation in mineable areas of the Powder River Basin is between 12 and 16 inches (Packer, 1975). A major concern is the general effect that increased mining activities has on water levels and flow direction, ground water recharge and discharge and changes in ground water chemistry. These parameters have not been sufficiently studied and consequently the effects of these changes are not known. It has been shown that ground and surface waters in other coal strip-mined areas in the United States can become highly acidic and ground water could also become contaminated (Hill, 1971; Cederstrom, 1971; USDI, 1967). Problems such as these could develop in the Powder River Basin.

Coal beds that will be mined in the Powder River Basin are up to 200 feet thick and are nearly horizontal. Many of the deposits which will be mined first are located in valley areas where overburden is thinnest. Most of the coal will be strip mined, and significant quantities of overlying shale, siltstone, and sandstone must be removed in order to mine the coal. Intermittent streams are temporarily diverted and the overburden will be ultimately dumped into mined out excavations (see Figure 2). Although leveling and terracing will be part of reclamation, compaction of the spoils will be limited and there will be a considerable increase in its volume from its original undisturbed state. According to mining engineers at the Decker Mine

(Robert A. Gjere, personal comm.), there is a 1.3 x increase in volume. In some places where thin sand and gravel deposits occur on top of the sedimentary rocks, the waste will include the gravel as well as ripped-up sedimentary rocks. In effect, the porosity and permeability of the waste should be considerably increased above its former undisturbed state. Depending on local geometry and position of the water table, these deposits may ultimately become saturated to various degrees by water, precipitation or percolating ground water.

In viewing the future of this land it is possible that the stripped and back-filled areas may become valuable man-made aquifers because of the increase in porosity and permeability of the waste rock. Some back-filled areas could be recharged with adjacent intermittent streams or with imported water. The positive value of the creation of a near-surface aquifer in this semi-arid region would be of considerable economic importance to the overall benefit-cost consideration of strip mining.

It is hoped that the results obtained from the present study will serve as guidelines for determining the potential of strip-mining fills as underground aquifers and water storage areas in the Powder River Basin.

The writer wishes to acknowledge the help of Mr. Paul J. Gerlach and Mr. Frank S. Farkas, graduate students at South Dakota School of Mines and Technology, who contributed significantly to the completion of this research. Mr. Dan Scott of the Padlock Ranch, Dayton, Wyoming, gave permission to study the Hidden Water Creek Mine. Most of the [redacted] coal companies were very cooperative. Special thanks goes to Mr. Michael Penz of the Peter Kiewit and Sons Company, Sheridan, Wyoming, for his

continuing help. Appreciation is extended to Mr. William J. Fogarty, project monitor of the Old West Regional Commission for his help and encouragment in this work. Dr. Jack A. Redden kindly helped in the planning of the project goals. [1]

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[1] This report is divided into five main tasks, in keeping with the original proposed outline submitted to the Old West Regional Commission.

TASK #1-POROSITY AND PERMEABILITY OF SPOILS

PREVIOUS TESTS

While there have been reports describing the hydraulic properties of aquifers in the Powder River Basin (e.g. USDI, 1974a; Lowry and Cummings, 1966; Whitcomb and Morris, 1964; Huntoon and Womack, 1975; Konikow, 1976), there is only one known published preliminary report by Rahn (1975) on infiltration tests and one known report by Van Voast (1973) that includes a description of a pump test in spoils in the Powder River Basin.

TWO PUMP TESTS IN SPOILS

In order to best determine the porosity and permeability of spoils, it is desirable to pump water from saturated deposits and to measure the drawdown in the water table in observation wells.

A reconnaisance survey of the existing strip-mines in the Powder River Basin showed that most of the mines are generally above the water table. Spoils such as at the Dave Johnston Mine north of Glenrock, Wyoming will not become saturated upon abandonment. Other mines, such as the Wyodak Mine near Gillette, Wyoming, although below the water table, are currently active: dewatering operations keep the spoils from becoming saturated. To the writer's knowledge, only two mines presently possess significant quantities of saturated spoils: the Bighorn and the Hidden Water Creek Mines north of Sheridan, Wyoming. Therefore these two areas were selected for the pump tests described below. The following description of the two pump tests are summarized from a more detailed report by Gerlach (1976).

Hidden Water Creek Mine Pump Test

The Hidden Water Creek coal mines are located about three miles

north of Monarch, Wyoming. The mines were worked about 20 years ago, and are now abandoned.

A 10 in. production well was drilled on June 16, 1975 in coal strip-mine spoils to a depth of 39 ft. in the NW¼SE¼ of Sec. 1, T. 57 N., R. 85 W. The well was gravel-packed with pea-gravel along its entire depth, and fitted with a 6 in. plastic casing that had been perforated from 23 to 39 ft. The perforations consisted of slots 6 in. long and ¼ in. wide, spaced at 4 in. intervals on two sides along the length of casing. The production well penetrated the entire thickness of spoils and intercepted solid coal at a depth of 33 ft. These spoils had been dragline emplaced, and are about 20 years old (Mr. Michael Penz, personal comm.). Figure 3 shows the Hidden Water Creek coal strip mine on the U.S. Geological Survey Monarch Quadrangle, 7.5 minute topographic map. Figure 4 is a geologic cross-section through the pump test site showing the sequence of coal beds within the Fort Union Group sediments.

Eleven 4 in. observation wells, N. 20° W. numbers 1,2,3,4, E. 22° S. numbers 1,2,3, and S. 85° W. numbers 1,2,3,4, were drilled on radials that came as close as possible to 120 degrees. Heavy rains combined with the topography of the test site made precise placement of the observation wells at 120 degree radials impossible (Figure 5). All observation wells penetrated approximately the entire thickness of spoils. Each observation well was fitted with a 2 in. plastic casing that had been perforated up to 14 ft. from the bottom of the casing. Figure 6 is a plane-table map showing the arrangement and spacing of the wells and the topography of the test area. Figure 7 shows the general topography of the test area. Note the conical piles of unvegetated dragline-dumped spoils in contrast with the undisturbed prairie.

After flushing the wells with water the water table was allowed to stabilize for 5½ days until pumping began 9:20 AM., June 23, 1975. A submersible water pump was used, and the pumped water was discharged to the pond 163 ft. southeast of the pumping well. Recirculation of the discharge water to the water table was not suspected. An initial pumping rate of 26 gpm was reduced to 20.7 gpm 23 minutes after the test began. This pumping rate was held constant for the duration of the 26.7 hour pump test.

The drawdown for each well was calculated by subtracting the pre-test static water-table level from the depth to the water table observed during the pump test. Water levels were read with a Soiltest electric water level indicator (Figure 8). The pre-test water table at observation well S. 85° W. no. 4 was not static, but was falling in response to the natural draining of a deep puddle of water adjacent to the well. Therefore it was necessary to extrapolate the trend of the pre-test water table at this well throughout the duration of the pump test. The drawdown at this observation well was calculated by subtracting the extrapolated water-table trend from the water table readings observed during the pump test.

Aquifer constants were determined using the leaky artesian formula as discussed by Walton (1962, p. 4-5). The time-drawdown curve for each observation well was superimposed over the leaky or non-leaky type curve that matched best, and the match coordinates were obtained. Time-drawdown curves and the resultant mathematical solution of transmissivity (T) and storage coefficient (S) for each observation well are included in Appendix I. It should be noted that the time-drawdown data curves for observation well S. 85° W. numbers 1 and 2, and N. 20° W. numbers 1,2,3, and 4 match leaky artesian-type curves. This suggests that for

these wells there was either (1) significant ground water leakage from the underlying Monarch (?) coal bed into the overlying spoils during the pump test, (2) a delay in the release of ground water in storage during pumping, or (3) induced infiltration of nearby pond water during pumping. The time-drawdown data curves for the remainder of the observation wells, wells S. 85° W. numbers 3 and 4, and E. 22° S. numbers 1,2, and 3 fit the non-leaky artesian-type curve. This would suggest that these wells were not influenced by factors that may produce leaky artesian-type curves. Figure 9 shows the drawdown after 1411 minutes of continous pumping, and Figure 10 is a cross-section through 8 of the wells showing the drawdown in relation to the static water table at this time. From Figure 9 it is obvious that the lines of equal drawdown are elongated northwest-southeast. This is parallel to the depression that is the original mine cut. As seen in Figure 9 a portion of this mine cut is occupied by two strip-mine ponds. The elongation of the drawdown contours in the directions of the strip-mine ponds indicates that there was little induced infiltration of pond water to the pumping well during the pump test. Had induced infiltration of pond water occured the drawdown contours would be close together (indicating a steep gradient for the cone of depression) in the directions of the two ponds. Using the time-drawdwon calculations the average value of T = 8,257 gpd/ft, and S = 0.128. A summary of aquifer constants is presented in Table 1. The specific capacity of the pumping well after 1411 minutes of pumping was 1.67 gpm/ft.

Distance-drawdown curves were plotted for each row of observation wells radiating from the production well, and for the three rows combined. Values of T and S were calculated after 0.98 days of pumping using the Jacob Method described in Walton (1962, p. 8,9). The

distance-drawdown curves and the resultant mathematical solution of T and S are included in Appendix I. Distance-drawdown values were plotted for the observation wells in row N. 20° W. after 0.98 and 0.54 days pumping, but the aquifer coefficients could not be calculated since the points do not describe a straight line as required in the Jacob Method. The aquifer constants derived from the distance-drawdown calculations are presented in Table 1. Using the distance-drawdown calculations the average T = 13, 850, and S = 0.212.

Averaging both the time-drawdown and distance-drawdown results gives T = 11,050 gpd/ft, and S = 0.170. The average saturated thickness of spoils in the test area is 24.5 ft.; therefore the coefficient of permeability (K) = 11,050/24.5 = 450 gpd/ft^2.

Water quality samples of the pump discharge water were taken after 1.95 hours of pumping, and after 26.42 hours of pumping. For comparison a sample of the water taken June 24 from the strip-mine pond 162 ft. southeast of the pumping well was also analyzed (Table 2). From a study of the three water analyses it is obvious that the ground water in the spoils is much more mineralized than the water in the mine pit. Also, the water in the spoils is acidic, whereas the water from the pond is basic. The chemical analysis of the discharge water taken at the beginning of the pump test is very similar to the analysis of the discharge water taken at the end of the pump test. Therefore, it is apparent that the source of water for the pumping well was not the strip-mine pond. The leaky artesian condition described by some of the time-drawdown data curves as discussed above was apparently not caused by induced infiltration of strip-mine pond water to the pumping well during the pump test.

Bighorn Pump Test

On July 7, 1975 the Peter Kiewit and Sons Company drilled a 7 7/8 in. diameter production well to a depth of 56 ft. in Bighorn coal mine spoils in the SE¼NW¼ of Sec. 22, T. 57 N., R. 84 W. These spoils have been bulldozer-scraper emplaced, and they are approximately 20 years old (Mr. Michael Penz, pers. comm.). The well was gravel-packed with pea-gravel its entire depth and fitted with a 5 in. plastic casing that had been perforated from 11 to 56 ft. The perforations consisted of slots 6 in. long and ¼ in. wide, spaced at 4 in. intervals on two sides along the length of the casing. The production well penetrated the entire thickness of spoils, intersecting undisturbed Tongue River Formation stratigraphy at a depth of 56 ft. Figure 11 shows the Bighorn coal mine as of 1968 on the U.S. Geological Survey Acme Quadrangle, 7.5 minute topographic map. Figure 12 is a geologic cross-section through the pump test site showing the approximate relations of the coal beds within the Fort Union Group sediments. Figure 13 shows the test site area.

Twelve 2 in. observation wells, N. 18° E. numbers 1,2,3,4,5, S. 48° E. numbers 1,2,3,4, and N. 75° W. numbers 1,2,3, drilled by Peter Kiewit and Sons Company, were placed on radials that came as close as possible to 120 degrees. All observation wells penetrated the entire thickness of spoils. Each observation well was fitted with a 2 in. plastic casing that had been perforated to within approximately 10 ft. of the surface of the spoils. Figure 14 is a plane-table map showing the arrangement and spacing of the wells, and the topography of the pump test site.

After thoroughly flushing the wells with water to remove remaining

drilling mud, the water table was allowed to stabilize for 3.5 days until 10 AM., July 14, 1975, when the pumping well was tested briefly to ascertain an approximate well yield. The final pump test began 9:12 AM., July 15, 1975. A submersible water pump was used, and the discharge water was discharged east to Goose Creek. An initial pumping rate of 4 gpm was increased to 6.5 gpm 42 minutes after the test began. This pumping rate was held constant for the duration of the 49.2 hour pump test.

Apart from the cone of depression caused by the pumping well, the water table at the Bighorn coal mine test site was not static, but was falling in response to the seasonal recession of Goose Creek. This caused complications in the determination of the exact amount of drawdown of the water table due to pumping during the aquifer test. It was necessary to plot the trend of the water table before and after the pump test, and to extrapolate that trend during the pump test. The drawdown of the water table during the pump test was calculated by subtracting the extrapolated water-table trend from the observed water table readings.

Aquifer constants were determined using the leaky artesian formula in the same manner as that described for the Hidden Water Creek Mine pump test. Of the twelve observation wells, only three, S. 48° E. 1,2 and N. 18° E. 3 showed sufficient drawdown to plot as conventional "type curves." Four of the remaining observation wells exhibited measurable (1 in. or more) drawdown only at the end of the pump test, and five wells had no drawdown at all. Time-drawdown curves and the resultant mathematical solutions for the three observation wells are included in Appendix II. The curves for these three observation wells plot as leaky artesian-type curves, probably indicating a delay in the

release of ground water in storage during pumping. Figure 15 is a map of the drawdown at the Bighorn mine pump test site after 2777 min. of continuous pumping. Figure 16 is a cross-section through ten of the wells showing the pre-test water table and the cone of depression of the water table after 2777 min. of pumping. Using the time-drawdown plots the average value of T = 172 gpd/ft, and S = 0.233. The specific capacity of the pumping well after 2777 min. of pumping was calculated to be 0.34 gpm/ft.

Distance-drawdown values observed after 0.98 and 2.04 days of pumping for observation wells showing a response to pumping, were plotted for each row of wells radiating from the production well. These plots are presented in Appendix II. Values of T and S for each row of observation wells could not be calculated because the plots of distance-drawdown values did not form a straight line as required in the Jacob Method (Walton, 1962, p. 8-9). A value of T and S was calculated for the distance-drawdown plot of the combination of all wells showing a response to pumping, but as the results were considered unreasonably high they were not included in the final tabulation.

Water quality samples of the pumping well discharge were taken after 1.10 and 32.80 hours pumping. For comparison, a water quality sample was taken in the Goose Creek pond adjacent to the pump test site on July 15, 1975. Rahn (1975, p. 361) reported on the quality of a ground water seep taken at the south end of the main active pit of the Bighorn mine, approximately 1800 ft. southeast of the pump test site. The analyses of these four water samples are given in Table 3. From Table 3 it is obvious that the ground water from the mine seep is high in sodium and sulfate, and is more mineralized than the ground water in the pump test spoils. The ground water in the pump test spoils is

probably derived in part from Goose Creek which has a low total dissolved solids content. The analysis of the pumping well discharge water taken after 1.10 hours of pumping shows little change from the analysis of the sample collected after 32.80 hours of pumping. Therefore the cone of depression of the pumping well apparently did not extend to the less mineralized water of Goose Creek, and methods of image well theory did not have to be employed. From a review of the time-drawdown curves for the observation wells of the Bighorn pump test presented in Appendix II it is apparent that the data points began to approach a leaky artesian-type curve after a maximum pumping time of 6.7 hours. This would indicate that the deviation of the time-drawdown curves from the type curve is due to some other reason other than recharge from Goose Creek. This deviation may have been caused by delayed gravity drainage of the dewatered portion of the spoils during the pump test (Prickett, 1965, p.9).

INFILTRATION TESTS

Because conventional pump tests could only be conducted at two coal strip mines, it was necessary to resort to another method of establishing hydraulic properties of the spoils in the other mines. This was accomplished through the study of field infiltration rates, spoils moisture content, grain size analyses, field density of the spoils, overburden lithology and laboratory calculation of permeability. Infiltration is the ability of a soil to absorb water (Horton, 1933), and is dependent on the permeability but also the antecedent moisture (Canarache, et al, 1969).

Spoils from six coal strip mines (Figure 1) were studied during the summer of 1975. The Wyodak and Belle Ayr Mines, located in the

southeastern Powder River Basin near Gillette, and the Bighorn Number One and Hidden Water Creek Mines, located in the western part of the Basin near Sheridan were selected as representatives of Wyoming coal strip mines. Additionally, spoils from the Decker Mine near Sheridan and Rosebud Mine near Colstrip were selected as being representatives of Montana mines.

The mines studied were chosen not only for their accessibility but also because they are the largest mines in the area and represent a good cross-section of the Powder River Basin with regard to variation in overburden lithology. The research detailed below is summarized from a detailed report by Farkas (1976).

For the purpose of this research, a set of five cylinder infiltrometers, also known as ring infiltrometers, were utilized to determine the water intake characteristics of the coal strip-mine spoils. The cylinders are constructed of 14 gauge smooth steel and measure 12 in. in length. Diameters vary from 10 to 12 in., thus enabling nesting of the rings. Emplacement of the cylinders was accomplished by placing a ½ in. thick, rectangular steel driving plate over the cylinder and while standing on the plate, tamping the plate with a 16 lb. driving hammer. The cylinders were driven six inches into the spoils to ensure minimum leakage. Following the procedure outlined by Haise and others (1956), the cylinders were spaced at 15 ft. intervals in various patterns, depending on the shape of the spoils piles (Figure 17). Water for the cylinders was obtained from barrels carried in the back of a truck or by hand-carrying it from a nearby pond. All five cylinders were used in areas where water supply was adequate. In no test were fewer than three cylinders used. Each cylinder was kept

filled with water to a depth of four to five in. to maintain the same head. Measurements were taken at the end of 5, 10, 20, 30, 45, 60, 90 and 120 minutes where possible. Higher intake spoils required more frequent readings. Tests were run two hours or until 6 in. of water were taken into the spoils (Haise and others, 1956, p. 6). When abnormally high or low readings were obtained, the cylinders were pulled out at the conclusion of the test and the spoils examined for possible causes.

Data from the tests is presented graphically as accumulated average intake, in inches of water, versus time, in minutes. Results for all 44 tests for the 6 mines studied are presented in Appendix III. It must be noted that, although the spoils represent mixed overburden and therefore the test sites can be considered to have random stratigraphic position, the same cannot be said for the aerial location of the test sites. Mining operations precluded entirely random selection of the infiltration sites. Further, it must be recognized that in no mine are the spoils entirely homogeneous. Various methods of spoils emplacement are used in the coal strip mines (Figure 18-19). Dragline-dumped spoils (Figure 18) are generally considered to be less compacted than scraper-dumped spoils, where scraper tires add to the spoils compaction.

Actual values showing the difference in densities for different styles of spoils emplacement were determined for each of the 44 sites. The value of the density was necessary for two reasons: first, to ascertain the effect of varying density on infiltration rate; and second, to duplicate field density in the laboratory permeability tests. With the laboratory apparatus packed to field density, more accurate estimates of field permeability could be made from the laboratory data. To determine the density at a particular test site, a small hole was

carefully dug in the spoils and all the samples saved in a sealed bag. Next, a sand of known density, 104.5 lb/ft^3 for all tests, was poured into the hole filling it to its original level. Knowing the weight of sand poured into the hole and the weight of sample extracted, the field density of the sample could be calculated. Field density results for all tests are presented in Table 4.

The moisture content of each density sample was obtained in order to correlate the values with their corresponding infiltration rates. A 1 lb. sample was taken from each density sample and oven dried at a temperature of 110° C for 16 hours as described by two Laboratory Soils Testing Manual (1970, p. 1-3). Moisture content was then calculated, (Peck and others, 1974, p. 11). Moisture content data are shown in Table 4.

Constant-head laboratory permeameter tests were run on each of the 44 samples collected in the field. Each sample was packed into a Soiltest model K-612 permeameter (Figure 20) to field density. Farkas (1976) showed that the most consistant permeability data could be obtained by compacting the sample by dropping the laboratory cylinder until field density could be obtained.

It has been noted in the literature (Davis and DeWiest, 1966; Fireman, 1944; Rahn, 1968) that the permeability of samples calculated from laboratory tests may not be the same as that obtained by pumping tests in the field. This is due primarily to the fact that, in removing the material from the field, the material is disturbed. Repacking it in the laboratory to its original state is, for all practical purposes, impossible. In this investigation, however, the field samples, being overburden spoils, are already disturbed in their natural state, thus greater correlation between field and laboratory data might be expected.

Darcy's law for flow of water through a soil medium was used for the calculation of laboratory permeabilities (Fireman, 1944, p. 338). Parameters and conversions used in the calculations are shown in Figure 21. Permeabilities obtained are presented in Table 4.

Dry sieve analyses were conducted on selected samples from the coal strip-mine spoils in the study area. Specifically, the samples from each mine showing the highest and lowest permeability, as determined by laboratory tests, and one of intermediate value were sieved. Samples were prepared using the method outlined by Folk (1968, p. 34) and sieved through number 35, 60, 120, 230 and 235 U.S. Standard mesh sieves. Results were plotted graphically as per cent finer by weight versus grain size according to procedures outlined in the (Laboratory Soils Testing Manual (1970, p. v-8) and appear in Appendix III.

Eighteen sieve analyses, three from each mine area studied, were conducted in order to establish grain size variations in an attempt to explain variations in permeability between samples that are similar in appearance. Graphs of results appear in Appendix III. Test samples FF-18, 24, 29, from the Rosebud Mine, show laboratory permeabilities of 57.6, 0.9 and 13.0 gpd/ft^2 respectively (Table 4). Graphs of grain size (Appendix III) for these tests reveal that sample FF-38 contains 10%, FF-20 contains 36% and FF-24 contains 18% silt size (0.0625mm) or smaller particles. Thus samples appearing similar in the field, when disaggregated, show that a higher percentage of silt size or smaller particles usually indicate a lower permeability.

Hidden Water Creek Mine

The Hidden Water Creek Mine (Sec. 1, T. 57 N., R. 85 W.), has a somewhat nebulous history. Little is known about actual production, but

it is known that the mine was closed in the early 1950's. The mine is in the Tongue River Member of the Fort Union Formation (Mapel, 1958, p. 233; Barnum, 1975). Overburden consists primarily of yellowish-brown sandstone interbedded with gray, carbonaceous shale. The spoils were emplaced in elongate hills by dragline and were, therefore, relatively uncompacted. The spoils hills have been exposed for a minimum of 25 years and weathering has produced a somewhat compacted clayey crust on the top few inches of the hills. Vegetation is sparse to nearly nonexistent, only noticeable during the rainy days of spring.

As seen in Figure 22, nine infiltration tests were conducted in the Hidden Water spoils. Appendix III contains the results of the infiltration studies. It can be noted that a few of the graphs show more than one curve. Test site FF-1, for example, shows the average infiltration rate for all five cylinders used in the test is 6 in/hr. As can be seen, of the five cylinders, two were located on an old haulage road. Those cylinders attained an average infiltration rate of only 0.2 in/hr. The remaining three cylinders averaged 10.0 in/hr. Therefore values of infiltration rate reported in Table 4 are considered to be the best estimate of the overall infiltration rate of the spoils-in this case, 10.0 in/hr. The infiltration rates thus estimated for all mines were calculated for the latter portion of the test where the slope of the infiltration rate versus time line attains a fairly constant slope. Infiltration rates for the nine test sites in the Hidden Water mine range from 1.4 to 10.0 in/hr with a mean of 4.4 in/hr (Table 4 and Appendix III).

Laboratory permeability values for the Hidden Water Creek Mine (Table 1) range from 0.9 to 48.0 gal/day/ft^2 with a mean of 10.0 gal/day/ft^2.

Bighorn Number One Mine

The Bighorn Mine (Secs. 15, 22, T. 57 N., R. 84 W.) is a subsidiary of Peter Kiewit and Sons Company. The mine, like the Hidden Water Mine, is in the Tongue River Member of the Fort Union Formation (Maple, 1958, p. 223) and has a similar overburden lithology. Bighorn uses scrapers, rather than dragline, for overburden removal and subsequent emplacement (Glass, 1973, p. 30).

Figure 22 shows the location of the eight infiltration test sites. Results of these tests are presented graphically in Appendix III. Test site FF-44 shows the variability in the spoils even within a small area. Due to the lack of water, only four cylinders were used in the test. With two cylinders in coaly spoils and two in noncoaly spoils the infiltration rate is 11.3 in/hr in coaly spoils; the two cylinders not in coaly spoils, on the other hand, show an infiltration rate of 3.6 in/hr. Infiltration rates at this mine (Table 4 and Appendix III) range from 0.3 to 17.6 in/hr with a mean of 3.5 in/hr.

Laboratory permeability values (Table 4) range from 2.3 to 22.8 gal/day/ft^2 with a mean of 9.6 gal/day/ft^2.

Rosebud Mine

Mining near Colstrip, Montana (Sec. 34, T. 2 N., R. 41 E.) began in 1924. The Northern Pacific Railway (now the Burlington Northern) mined coal for its steam locomotives until 1958 when diesel power came of age. In 1958, Montana Power and Light Company, Inc. acquired the Northern Pacific's mining leases. Western Energy Company, a subsidiary of Montana Power, later acquired additional leases in the Colstrip area. Coal mining in the Colstrip area will accelerate in the next decades and the U.S. Department of Interior is in the process of preparing an environmental impact statement for this area.

Coal from the Rosebud Mine comes predominantly from the Rosebud seam in the Tongue River Member of the Fort Union Formation (Matson and Blumer, 1973, p. 77). Overburden, which is removed primarily by dragline, following removal and stockpiling of topsoil, consists of upper Fort Union Formation, principally fine-grained sandstone, gray shale and siltstone.

Figure 23 shows the locations of the eight infiltration test sites in the Colstrip area. Results are presented graphically in Appendix III. Infiltration rates (Table 4 and Appendix III) range from 0.2 to 3.4 in/hr with a mean of 1.3 in/hr. The graph of results for test site FF-17 (Appendix III) shows the effect of one cylinder being inadvertently atop a subsurface fissure. Eliminating that cylinder from the calculations, the infiltration rate for the remaining four cylinders is 2.0 in/hr, 1.6 in/hr less than if results from all five cylinders are utilized.

Laboratory permeability values (Table 4) range from 0.9 to 57.6 gal/day/ft^2 with an average of 10.4 gal/day/ft^2.

Decker Mine

The Decker Mine (Secs. 9, 15, 16, T. 9 S., R. 40 E.), operated by Peter Kiewit and Sons, Inc. as a joint venture with Pacific Power and Light Company, was opened in August 1972. The mine is located in the Tongue River Member of the Fort Union Formation (Matson and Blumer, 1973). Coal is mined from the 50 ft. thick seam designated the D-1 coal by the Decker Coal Company personnel. Overburden in the mine area consists primarily of discontinous beds of silt, silty shale and fine-grained sand and sandstone (Van Voast, 1974, p.6). After the topsoil has been salvaged, the overburden is drilled, shot with explosives and removed by dragline. After mining the spoils are then contoured by

bulldozer and the topsoil replaced (Figure 24).

Figure 25 shows the approximate location of the eight infiltration test sites. Results are presented graphically in Appendix III. Infiltration rates (Table 4 and Appendix IV) on contoured spoils range from 0.2 to 0.4 in/hr with a mean of 0.3 in/hr. Test sites FF-27 and 28, located on spoils banks prior to their being contoured, have average infiltration values of 37.5 and 10.0 in/hr. This is no doubt due to the prescence of fissures in the spoils as well as the fact that the compaction from the bulldozing of the piles has not yet occured.

Laboratory permeabilities range from 0.4 to 1.5 gal/day/ft^2 with an average of 0.9 gal/day/ft^2.

Wyodak Mine

The Wyodak Mine (Secs. 27, 28, T. 50 N., R. 71 W.) opened in 1925 and, since that time, has produced coal under a number of owners. Coal is mined from the Roland and Smith beds whose average combined thickness is approximately 70 feet (Glass, 1973, p. 31). As the Roland seam is considered to be the top of the Fort Union Formation (Brown, 1958, p. 112), the overburden is then Wasatch Formation and alluvium. In the mine area the overburden ranges from 15 to 40 ft. in thickness and consists primarily of lenticular, fine-grained sandstone, gray clay and silty clay. In addition, varying amounts of Quaternary alluvium, consisting of sand, silt, clay and thin layers of gravel, derived from fragments of clinker, red shale and pieces of hard, fine-grained sandstone, are present in stream valleys in the area (Swenson, 1950, p. 9). The overburden is removed by scraper and used as back fill in the mined-out areas of the mine.

Due to the limited amount of spoils, only six infiltration tests

were conducted. Their locations are shown in Figure 27. Results of the infiltration tests are presented in Appendix III. Infiltration rates (Table 1 and Appendix III) range from 0.6 to 25.7 in/hr with a mean of 6.4 in/hr.

Laboratory permeability values on six samples (Table 4) range from 6.6 to 38.0 gal/day/ft^2 with an average of 14.8 gal/day/ft^2.

Belle Ayr Mine

The Belle Ayr Mine (Secs. 33, 34, T. 48 N., R. 71 W.), owned by the Amax Coal Company, is located 15 miles south of the Wyodak mine. Coal is produced from the Roland-Smith beds in the Tongue River Member of the Fort Union Formation. The beds have a combined average thickness of 70 ft. in the mine area (U.S. Geological Survey, 1975, p. 53). Overburden, from the Wasatch Formation, consisting of gray shale, yellow-brown sandstone and gray siltstone, along with varying amounts of Quaternary alluvium, is removed by a bucket wheel excavator and scrapers. It is transported to the dump site by truck (Figure 19) and leveled by bulldozer or road graders. In the area of current mining, the overburden varies from 15 to over 100 ft. in thickness.

Figure 28 shows the approximate locations of the five infiltration test sites in the Belle Ayr area. The locations are only approximate as the size and shape of the pit and location of the spoils are constantly changing, as in all the active mines investigated. Results from these test sites are presented graphically in Appendix III. Infiltration rates (Table 4 and Appendix III) range from 1.8 to 39.7 gal/day/ft^2 with an average of 12.9 gal/day/ft^2.

Laboratory permeability values (Table 4 and Appendix III) range from 1.8 to 39.7 gal/day/ft^2 with an average of 12.9 gal/day/ft^2.

DISCUSSION OF POROSITY AND PERMEABILITY

The two pump tests, at the Hidden Water Creek and Bighorn Mines, both showed time-drawdown plots that have a deviation from the expected "type curve". In pump tests of water-table aquifers the deviation of the time-drawdown data curves from the nonleaky artesian-type curve may be caused by (1) delayed gravity drainage of the dewatered portion of the aquifer, (2) induced infiltration from an adjacent recharge boundary, or (3) recharge from an underlying aquifer. [redacted] Figure 29 illustrates the three probable ways leaky artesian conditions may be obtained during the pumping of a water-table aquifer. As previously discussed, induced infiltration of strip-mine pond waters was apparently not the cause for the leaky artesian conditions of some of the observation wells at either the Hidden Water Creek Mine or Bighorn Mine pump tests. Therefore, leaky artesian conditions obtained at both mines are believed to be the result of delayed gravity drainage of the dewatered portion of the spoils, or to a lesser degree recharge from possible underlying coal beds or permeable rubble at the base of the spoils.

Prickett (1965, p. 12) reported that delays in the release of ground water in storage during pumping will cause time-drawdown data curves to describe leaky artesian curves for approximately 1 hour to several days depending upon whether the aquifer material is composed predominantly of coarse to medium size sand, or very fine sand to silt. Strip-mine spoils are composed of an extremely nonhomogeneous mixture of clay to gravel-size particle grains. Observation wells with time-drawdown data curves describing leaky artesian conditions may represent areas of more clayey spoils in which delayed gravity drainage is

effective for up to several days after pumping began. Observation wells with time-drawdown data curves describing nonleaky artesian conditions may represent areas of more sandy spoils in which delayed gravity drainage is effective for only several hours or less. After a short initial period of pumping the drainage of areas of more sandy spoils tends to catch up with the rate of fall of the water table and time-drawdown data curves describe the nonleaky artesian-type curve.

The nonhomogeneous nature of spoils is clearly evident in analysis of water-table drawdown values obtained during the Bighorn mine pump test. After 2777 minutes of continous pumping, drawdown was observed at observation wells N. 18° E. 1, 3, and 5, but no drawdown was observed at intermediate wells 2 and 4 (see Figure 15). The spoils at observation wells N. 18° E. 2 and 4 may be very clayey, not readily yielding water to a small decline in the ground water table. Figure 16 shows an interpretation of the heterogeneity of the spoils which may have caused the irregularities in drawdown observed at observation wells during the pump test.

In summary, the results of the two pump tests indicate average permeabilities and storage coefficients of 450 gpd/ft^2 and 0.170 for the Hidden Water coal mine spoils, and 4 gpd/ft^2 and 0.233 for the Bighorn coal mine spoils. These values can be compared to the permeability and storage in undisturbed Tertiary sedimentary rocks. From analysis of two pump tests in sandstone aquifers of the Fort Union Group in Wyoming, Lowry and Cummings (1966, p. 20-21) reported values of permeability equal to 7.9 and 2.5 gpd/ft^2, and values of storage equal to 3.5×10^{-4} and 9×10^{-5}. Such low storage coefficients are indicative of aquifers under artesian pressure, whereas higher storage

coefficients, such as those of the Hidden Water Creek and Bighorn Mine pump tests, are indicative of water-table aquifers. Lowry and Cummings also reported that 61 percent of 88 wells tested in the Fort Union Group had specific capacities of between 0.1 and 1.0 gpm/ft. (See Appendix VI for miscellaneous pump test data). This data on natural, shallow sandstone aquifers is comparable to the specific capacity for spoils calculated for the Bighorn Mine pumping well. Only 11 percent of the wells reported by Lowry and Cummings had specific capacities as great as, or greater than that calculated for the Hidden Water Creek pumping well. Other sandstone aquifer tests supported this conclusion. Whitcomb and Morris (1964, p. 15) found a range in values of specific capacities between .09 and 0.56 gpm/ft. based on the aquifer coefficients of four pump tests in Fort Union Group aquifers, western Crook County, Wyoming. Whitcomb and Morris (p. 40) also reported that pumping tests in the Fort Union Group near Gillette, Wyoming yielded an average value of permeability of 3 gpd/ft^2, and an average specific capacity of 0.9 gpm/ft. Van Voast (1973) reported a permeability range of 0.5 to 50 gpd/ft^2 from studies still in progress, of the coal strip-mine spoils derived from mining in the Tongue River Formation near Colstrip, Montana.

The lack of bedding and sorting of sediment grains in spoils would tend to suggest that the permeability of spoils should be less than that of an undisturbed, bedded sediment of the same material. In the natural sedimentary environment the highest permeabilities are generally found in aquifers with well-sorted, bedded sediments of coarse sand to gravel-size grains (Davis and DeWiest, 1966, p. 374-380). The value of average permeability, 4 gpd/ft^2, obtained for the Bighorn Mine

pump test is in close agreement with permeabilities calculated for undisturbed Fort Union Group sand beds elsewhere in the Powder River Basin. The large value of permeability obtained for the Hidden Water Creek mine pump test, 450 gpd/ft^2, is in agreement with what might be expected for a bedded sediment composed predominantly of fone sand-size grains (Davis and DeWiest, 1966, p. 375). This large permeability mav be due to the method of emplacement ef the spoils. The laboratory tests show that the permeability anv sample of spoils is largely dependent upon the compaction, and therefore, method of emplacement of the spoils. Spoils such as those of the Hidden Water Creek mine, which were dragline emplaced and are loosely compacted should have higher permeabilities than compacted bulldozer-scraper emplaced spoils, such as those of the Bighorn mine. Another factor that may account for the higher permeability of the Hidden Water Creek spoils is that during the dragline-dumping of spoils, boulders and cobbles tend to roll down the side of the spoil piles, creating a laver of coarse rubble at the base of the spoils. This phenomenon was observed at the Decker Mine at Decker, Montana, and the Rosebud coal mine near Colstrip, Montana. A laver of coarse rubble could represent a zone of higher ground water permeability under a pile of dragline-emplaced spoils.

The conclusion based on the two pump tests described above that permeability depends on compaction is also generally supported by laboratory permeability data. Farkas (1976) has shown that in a general way as the density increases, the infiltration rate decreases. The style of compaction and composition of spoils appears to be more important than the actual density of the spoils, however. To illustrate, a clay with a density of 80 lb/ft^3 in nature, if compacted to 100 lb/ft^3 in a

spoils pile, would show a much smaller infiltration rate than a fine to medium-grained sand with a density of 120 lb/ft^3.

Analysis of the field data from the 6 mines also supports this conclusion. The density values (Table 4) from mines where spoils are emplaced by dragline (Rosebud, Decker, and Hidden Water Creek Mines) averages 91 lb/ft^3. (Note: this value does not include density values obtained from test sites on bulldozer-contoured spoils at these mines, where the bulldozers have compacted the dragline emplaced spoils. See Table 4 and tests FF-19, 20, 21, 23, 25, 26, 30, 31, 32). At the Bighorn, Wyodak and Belle Ayr Mines, where spoils of similar lithologies are emplaced by scraper or truck, the average density of the spoils is approximately 102 lb/ft^3. It can be concluded that if less dense spoils are desired, emplacement by dragline is recommended.

Figure 30 shows a single graph of values of all average infiltration rates from 44 test sites versus laboratory permeabilities. This includes all six mines studied. The regression coefficient passes the test of significance at 90% confidence limits. The regression line and associated confidence limits show that field infiltration rates increase as the laboratory permeability increases, and may be estimated with 90% confidence for all of the mine spoils studied in the Powder River Basin.

Table 5 shows the data from Figure 30 summarized according to the 6 mines. The average infiltration rate and laboratory permeability of the 3 dragline-dumped spoils is 3.0 in/hr and 10.1 gpd/ft^2, respectively; the average infiltration rate and laboratory permeability of the 3 scraper and truck-dumped spoils is 7.6 in/hr and 12.4 gpd/ft^2, respectively. These figures, while confirming the fact that spoils with

larger field infiltration rates have larger laboratory permeabilities, seems to contradict the conclusion that scraper or truck-dumped spoils have lower permeabilities than dragline-dumped spoils. However the reason for this apparent contradiction is believed to be partly due to the fact that the overburden lithology at the three mines having scraper-dumped spoils contains more sandstone mines (see Task 2 below for description of overburden). Additionally, the field infiltration may not represent the entire spoils in that in dragline-dumped spoils a coarse rubble layer tends to form at the bottom of the spoils due to large (generally sandstone) blocks rolling to the bottom of the excavation. This rubble layer could account for the large pump test permeability of the Hidden Valley mine, as compared to the Bighorn mine while the lab permeability and field infiltration tests on the surface of these same spoils showed little difference in lab permeability or field infiltration between the two mines.

In summary, then, on the basis of 2 pump tests, 44 field infiltration tests, and lab permeability tests, it can be said that all other things being equal, dragline-dumped spoils have permeability and effective porosity many times that of natural, shallow sandstone aquifers within the Tongue River Formation (except for clinker beds to be discussed in Task 4 below). The permeability of truck-dumped spoils are about the same as natural sandstone aquifers.

TASK #2-SPOILS COMPOSITION

GENERAL STRATIGRAPHY

The Powder River Basin is a large trough which generally subsided seventy to thirty million years ago, and received great thicknesses of continental sediments. The Basin is asymmetric, its axis located to the west of center of the Basin (see detailed map in Hodson, et al, 1973, and USDI, 1975). Precambrian rocks attain an elevation of 13,167 ft. in the Cloud Peak area in the Bighorn Mountains whereas in the deepest part of the basin, 15 miles west of Pumpkin Buttes (T. 43 N., R. 75 W.), the basement rocks are at an elevation of 11,000 ft. below sea level. Topographically, the basin has low to moderate relief; elevations ranging from 4,000 to 6,000 ft. above sea level (Farkas, 1976, p. 6).

Coal strip mining in the Powder River Basin is largely confined to the Paleocene Fort Union and Eocene Wasatch Formations. For this reason, discussion of stratigraphy will be limited to these formations. Outcrops of the Fort Union Formation almost entirely encircle the Powder River Basin. In Wyoming, the Formation is divided into a lower Tullock Member, an intermediate Lebo and an upper Tongue River Member. East of Miles City in Montana, the Tullock and Lebo Members are combined and called the Ludlow Member (Figure 31). In Montana and the Dakotas, an additional member, the Sentinel Butte, overlies the Tongue River Member (Brown, 1958, p. 111).

The Tullock Member decreases from 1100 ft. in thickness in the southern Powder River Basin of Wyoming to around 250 ft. in the northern portion of the basin in Montana. The member is comprised of friable gray to yellowish-gray sandstone, gray shale, sandy shale and thin beds of coal. The contact between the Tullock Member and the underlying

Lance or Hell Creek Formations of Cretaceous age is generally agreed upon as the base of the lowest coal zone above the last evidence of dinosaur remains (Brown, 1958, p. 112).

The Lebo Member consists of from 150 to 400 ft. of dark gray shale interbedded with sandstone, siltstone and a few thin coal beds.

The Tongue River Member varies in thickness from 2,000 ft. in southern Montana to around 600 ft. in the Gillette, Wyoming area. It consists primarily of thick bedded, nonmarine, yellow-brown sandstones. Most of the strippable coal in the Powder River Basin is contained in this member (Mapel, 1958, p. 220). All of the mines studied in this report are located in the Tongue River Member.

The Wasatch Formation of Eocene age attains a maximum thickness of 2,000 ft. in the southern Powder River Basin. It consists primarily of yellow to gray sandstone, gray shale and beds of coal. The formation is lithologicallv similar to the underlying Tongue River Member of the Fort Union Formation (Mapel, 1958, p. 221). Except for the western edge of the Basin, where the Wasatch is mostly conglomerate and unconformable, the Wasatch conformably overlies the Fort Union Formation. In most areas the contact between the two formations is placed at the top of the Roland coal bed, or its equivalent, for lack of a structural or stratigraphic break (Love, 1952, p. 3).

The source for most of these early Tertiary sediment is generally believed to be the Bighorn Mountains to the west. The Wasatch Formation, for instance, is a coarse conglomerate along the foothills of the Bighorn Mountains near Story, Wyoming, but rapidly becomes finer grained within a few miles towards the east. Theoretically those coal mines closer to the Bighorn Mountains would contain overburden that would

be coarser, hence more permeable, than mines further east. Detailed examination of the stratigraphy of the overburden at the existing and proposed coal mines is presented below, and shows that this hypothesis is not true.

OVERBURDEN AT COAL MINES

Appendix IV shows typical geologic cross-sections of existing coal mines. These sections are representatives of the working faces of the open cuts during 1974 to 1976. Because the overburden varies from place to place in any coal mine, there is a large variation in the cross-sections within any mine (see Figure 32). Note, for instance, the contrast in the overburden at three sides of the Wyodak Mine (Appendix IV).

Nevertheless, Appendix IV provides a general indication of the overburden lithology. The lithology of coal strip-mine spoils (Gerlach, 1976, p. 15), is generally a random mixture of the sediment found overlying or between the mined coal beds, plus a variable concentration of crushed coal and clinker. The spoils may be loose or compacted depending on whether the spoils were dragline emplaced or bulldozer-scraper emplaced.

Appendix IV also shows well logs for proposed coal mines. These logs were kindly supplied by the individual coal companies or Environmental Impact Statements for the mines.

SUMMARY OF SPOILS COMPOSITION

In general the spoils at coal mines in the Powder River Basin contain semi-consolidated shale, siltstone, and sandstone from the Tongue River or Wasatch Formation. The shale breaks up and weathers rapidly upon mining and exposure to the air, and the spoils tend to be

very clayey and impassible to vehicle or pedestrian when wet.

At most coal mines, there is abundant clinker ("scoria"), produced by prehistoric burning of the coal beds. This clinker is generally brick red, and is a brecciated baked shale, siltstone, and sandstone. It is commonly quarried for road aggregate and railroad ballast in the Powder River Basin. Based on visual appearance, and the presence of closed topographic depressions above clinker areas, the clinker appears to be very permeable, and, where considerable amounts of clinker are added to the spoils, should tend to make the spoils more permeable.

Another constituent of coal spoils is crushed coal itself, or carboniferous shale, which was inadvertantly or deliberately wasted (see Figure 19).

Miscellaneous constituents in the spoils occassionally include petrified wood, gypsum crystals, and pyrite masses. Appendix IV shows the description of various samples obtained at the mines.

A semi-quantitative comparison of the lithologies of the overburden between all existing and proposed mines is given in Table 6. This shows the ratio of the thickness of coarse-grained to fine-grained sediments for each mine. The permeability factor herein described is a simple parameter used to quantify the relative permeability of the overburden based on grain size. The permeability factor is simply the ratios of the overburden thickness of sediments equal or coarser-grained than sandstone to the thickness of sediments equal or finer-grained than shale. The data on the grain size collected for this report may not be accurately representatives, especially for proposed mines where the overburden is known only by drill hole data supplied by mining companies. Because of great variation in lithology between open cuts in existing mines or between cores in proposed mines (Larry Messinger,

pers. comm.), Table 6 may not be very accurate. From Table 6, it can be stated that, all other things being equal, the mine studied having the coarsest-grained, hense most permeable, overburden is the Dave Johnston Mine. The finest-grained, hence least permeable, overburden is the Amax North Mine. The data shows that there is no correlation between grain size in mines studied and distance of mine from the Bighorn Mountains.

TASK #3-WATER COMPOSITION

Much has been written about the poor quality of surface and ground water which typically results from coal mining. Most of the area mined for coal in the United States is in the eastern states such as Pennsylvania, West Virginia, and Illinois. Sulfur, in the form of pyrite (FeS_2) scattered in the coal, oxidizes and coupled with high precipitation, (30 to 40 in/year) leads to the formation of dilute sulfuric acid, among other things, in the drain waters of many eastern coal fields (Vimmerstedt, et al, 1973). Waters are typically rusty in color and stream bottoms have red and yellow precipitates. Thousands of miles of streams are devoid of wildlife and vegetation and seriously affected by coal mining operations in the eastern states (USDI, 1967).

In the arid Powder River Basin, where the precipitation averages only about 14 in/year, and the coal is low in sulfur, it would appear that the same magnitude of water quality problem may not exist. This section of the report presents data in support of this conclusion.

GENERAL WATER QUALITY

Much data has already been published on water quality in this area. Pearl and Druse (1974) published data on water quality in the Powder River Basin. Littleton and Swenson (1950) showed that water quality is generally better in surficial aquifers near Gillette than in deep aquifers. Abundant data is published in a report by the Wyoming State Engineers (1972) and the U.S. Geological Survey (Hodson, et al, 1973). Because water quality may be biased by laboratory or sampling procedure, only samples collected first-hand and analyzed by the same laboratory are used in this paper. In general the data conforms to water quality from shallow aquifers in the northern Great Plains (USDI, 1975; Hodson, 1971).

Table 7 shows chemical data for 32 samples of water analyzed during 1974 to 1976. All samples were analyzed by the South Dakota School of Mines and Technology Mining and Engineering Experiment Station under the supervision of Dr. Amos L. Lingard. Analyses included the standard chemical data for all 32 samples; 2 samples were also analyzed for trace elements.

Table 7 also shows the maximum recommended drinking water limits established by the U.S. Public Health Service. Some ions, such as flouride, arsenic, cadmium, and mercury, are toxic to people if dissolved in drinking water. Other ions such as iron and manganese, cause inconveniences such as discoloration of water or clothes washed in the water. Some ions, such as sodium, calcium, and sulfate cause bad taste or temporary gastric distress. Ions such as silica and aluminum are not harmful in drinking water.

For ease of comparison, Table 7 shows those elements that have greater than the recommended drinking water limits (shown by "x"), those greater than 3 times the recommended drinking water limits shown by "y"), and those greater than 10 times the drinking water limits shown by "z"). Examination of Table 6 shows that the total dissolved solids is high for almost all samples, and that sulfate, and to a lesser degree calcium, magnesium, and manganese are also quite high. In general the water is hard and basic in pH. Iron, potassium, chloride, and nitrate are typically low. The only trace element which showed an amount greater than the recommended drinking water limit is cadmium.

In order to visually compare the distribution of the data for each substance analyzed, and the variation from the mean, frequency histograms of the common substances were constructed (see Appendix V). The mean

and standard deviation of the samples are also shown. From the frequency distributions, a cummulative frequency curve can be constructed for each analyzed substance; Figure 33 is a composite cummulative frequency curve for all substances. From Figure 33 it is possible to quickly summarize the most abundant ions in the 32 samples measured. The total dissolved solids of the water is high, because of large amounts of sulfate, calcium, and magnesium ions. Histograms for trace elements were not constructed because of insufficient data.

DISCUSSION OF QUALITY OF SURFACE, GROUND, AND SPOILS WATER

In order to assess the efects of strip mining on water quality, 28 of the 32 water samples were divided into three groups: (1) four samples collected from surface waters (streams and lakes) included OW-9,12,26, and 27; (2) sixteen samples collected from existing wells, or springs which indicate natural ground water include OW-1,2,3,4,5,6, 11,16,18,19,21,22,23,30,31, and 32; (3) eight samples obtained from pump tests in spoils include OW-8,10,13,14,15,17,24, and 28. Four samples (OW-7,20,25, and 29) were not included in these three groups because they are replicates or believed to be mixtures of other samples.

Appendix V shows histograms of the frequency distribution of 15 substances for each of these 3 groups. The mean and standard deviation are also shown. From these curves it is evident that ground water (GW) and water found in spoils (SP) have a higher total dissolved solids than surface water (SW).

Statistical tests were undertaken to determine the significance of the differences between the 3 groups described above. A "t" test was used to test the hypothesis that there is no difference between the

means. A 95% level of confidence was used for all tests of any two groups tested. For any given substance, then, there would be three such tests. Table 7 summarizes these 3 tests foi all 15 substances statistically analyzed. From Table 7 it is apparent that:

(1) Surface water is not different in mineral content than natural ground water for all 15 tests. (2) Surface water is not different in mineral content from spoils water in 9 to 15 properties compared. Spoils water is more mineralized than surface water in terms of total dissolved solids, total hardness, calcium, sulfate, and silica. (3) Water from spoils was found to contain significantly greater mineral properties than ground water in 5 of 18 tests, including total dissolved solids, total hardness, calcium, magnesium, and sulfate.

RELATIONSHIP OF SPOILS TO WATER QUALITY

Task 2, composition of spoils, showed that the spoils resulted from the stripping and dumping of the Fort Union and Wasatch Formation sedimentary rocks. These rocks are generally broken during mining, thus allowing fresh mineral surfaces to be exposed to percolating waters. While precise hydro-geochemical reactions are difficult to predict, it can be stated with some certainty that the equilibrium soil-water-mineral conditions which had been established by nature over thousands of years are changed by mining, and with the initiation of infiltrating rain water or percolating ground water in the spoils, more rapid weathering reactions can commence. Some rocks, in a subaqueous environment below the water table prior to mining, were placed above the water table in a subaerial environment after emplacement of spoils. Thus oxidizing reactions can occur more easily.

The most soluble mineral commonly found in the spoils is gypsum ($Ca\ So_4 \cdot 2\ H_2O$). Gypsum occurs in the spoils as massive clear crystal masses up to 6 in. long at some mines (eg: Wyodak), and smaller crystals are present in all existing mines studied. While gypsum constitutes probably less than 0.1% of the volume of the spoils, it is believed that the rapid solution of gypsum causes the high calcium and sulfate found in the ground and spoils water.

The high magnesium of the spoils water is enigmatic as there is little dolomite in these rocks. Magnesium may originate from the solution of epsomite, a hydrated magnesium sulfate (epsom salts), or from the weathering of the clay mineral montmorillimite, a mineral found in x-ray analyses of most of the samples.

Manganese is typically high in most samples. In the well in spoils at the Hidden Water Creek pump test site manganese reached 10 ppm, which is 200 times greater than the recommended drinking water limit. The source of manganese is not known, but could be due to the weathering of pyrolusite or psilomelane.

The pH of all waters tested is basic, except for the pumped well at Hidden Water spoils. Basic water is typical of this arid land. Apparently there is insufficient pyrite present to form enough sulfuric acid to counteract this condition. The low iron in all samples confirms that pyrite is not being weathered in appreciable quantities. From an environmental point of view, basic (non-acidic) and low iron water are desireable, although objectionable very high alkaline waters also containing high concentrations of sulfate, magnesium, manganese, and sodium have been reported by other workers (Hill, 1971).

In terms of water quality requirements for irrigation (Davis and DeWeist, 1966), natural ground water, surface water, and spoils exceed

the maximum recommended concentration for sulfate (500 ppm), and spoils exceed the maximum recommended concentration for total dissolved solids (3000 ppm). Both spoils and ground water are barely acceptable in terms of sodium (300 ppm).

In summary, it would appear that the quality of water found in the spoils may be a serious deterent to the usefulness of these waters. Spoils water is significantly more mineralized than natural ground water from shallow aquifers in terms of total dissolved solids and sulfate. Spoils water exceeds the recommended drinking water limits for both substances. It is doubtful that land could sustain long-term irrigation using these present waters. The water would have industrial or recreational use; for instance the highly mineralized water found in tailings ponds (OW-12, 26) does support bass and sunfish.

TASK #4-GROUND-WATER RECHARGE AND RELATIVE PERMEABILITY OF SPOILS, COAL, CLINKER, AND OVERBURDEN

In order to determine the practicality of using abandoned spoils for sources of ground water or for areas where ground water can be artificially recharged, it is necessary to predict the position of the water table in the abandoned spoils after mining has ceased.

Figure 34 is a sketch showing three stages in the idealized development of a coal mine in the Powder River Basin:

(1) Before mining occurs, the water table is shown above the coal bed; the coal is completely saturated with ground water. Clinker formed by the baking of shale, siltstone, and sandstone overburden, is shown to be partially saturated.

Clinker is formed by the burning of coal, generally in prehistoric times. Some "coal-crop fires" have been burning this century (Breckenridge, et al, 1974). The overburden becomes baked brick-red in color, and as the burning coal underneath decreases in volume, the clinker collapses into a chaotic jumble of loosely cemented breccia rubble. It is unlikely that coal could burn below much the water table; therefore the fact that saturated clinker beds are found today suggests a lower water table in the past. This mav have occured during the hot and arid altithermal interval of earth's history, 6500 to 4000 years ago, during which time even the Great Basin Lakes (Great Salt Lake, etc.) dried up (Baumhoff and Heizer, 1965). The basin of Lake DeSmet, a natural lake formed by burning coal (see Figure 1) could only have formed during a vastly more arid climate.

The reason why most active and proposed coal mines in the Powder River Basin are under flood plains of larger streams is because the coal has remained saturated, and thus was not burned throughout the Quaternary period. In interfluve hilly areas the water table is deeper and the coal has generally burned to considerable depth. The overburden to coal thickness ratios are greater than about 5:1, and hence the coal is not as economical to mine as in the valleys at this time.

(2) During mining, the overburden is generally transported to the mined out area and deposited as spoils. The mine is kept dry by pumps which may lower the water table for a considerable distance around the mine, depending on the permeability of the coal and overburden. It is during this time that spontaneous combustion of the coal (Figure 35) may occur, caused possibly by exothermic oxidation reactions accompanying the drying of previously saturated coal and exposure to air.

(3) After mining, the water table tends to rise to approximately its former level. In Figure 34 no spoils are shown against the working face. This area would simply become a lake.

Portions of spoils at the Hidden Valley and Bighorn Mine are presently saturated. Figures 4 and 10 are cross-sections where pump tests were run in saturated spoils to determine T and S. (Goose Creek actually flows through the lake shown at the Bighorn Mine). Present and future water table levels for other mines are discussed in Task 5 below.

There are five hydrogeologic areas shown "after mining" on Figure 34: undisturbed overburden, coal, the lake, spoils, and clinker. The yield that could be expected from wells shown in these five areas is assessed as follows:

(1) Available permeability and storage data of the undisturbed Fort Union strata is presented under Task #1 above. This data is summarized in Table 9. Specific capacity data is the amount of drawdown in a well pumping a given discharge, and is useful for comparing the data in Table 9. In general, the coefficient of transmissivity (T) for artesian and water table aquifers ranges from approximately 2,000 to 1,000 times the specific capacity after pumping for 1 day, respectively (Walton, 1962). The coefficient of permeability (K) equals T divided by the aquifer thickness (b). The average specific capacity of wells in the Fort Union Formation is about 0.4 gpm/ft of drawdown.

(2) The permeability of coal is difficult to assess. According to the National Academy of Science (1974, p. 45), and other publications coal is a good aquifer in the Gillette and other areas. This conclusion is supported by many local ranchers and well-drillers. Yet data collected at the Wyodak Mine (Appendix VI) shows that the coal is not very permeable. While it is beyond the scope of this report to determine the permeability of coal in the entire Powder River Basin, an estimate at the average specific capacity of wells in coal based on existing information is 1 gpm/ft, with great variation around the mean.

(3) Drawdown from the lake is limited only by the recharge to the lake. It has infinite permeability and specific capacity.

(4) The specific capacity of spoils studied in this research project range from 0.3 for truck and scraper-dumped spoils to 1.7 gpm/ft for dragline-dumped spoils.

(5) Clinker beds were found to be amazingly productive aquifers where saturated. Appendix VI describes a 153 ft. deep water well drilled for I-90 construction 2 mi. northwest of the Wyodak Mine at Gillette. The drawdown from pumping 360 gpm for 24 hours was only 20 ft., yielding a specific capacity of 18 gpm/ft. The areal extent of clinker beds in the Powder River is not known. They are found near the coal beds and are used as sources of aggregate (Breckenridge, et al, 1974).

In terms of relative permeability, the surficial deposits shown in Figure 34 and Table 9 can be summarized using mostly specific capacity data. The ratio of permeability of clinker, dragline-dumped spoils, coal, undisturbed overburden, and scraper-dumped spoils, is roughly 20/2/1/0.4/0.3. These permeabilities vary greatly from mine to mine, but the ratios are useful for general comparative purpose.

TASK #5-RECHARGE SITES

The goal of Task 5 of this research project is to delineate specific mines where useful ground supplies could be obtained upon abandonment.

Figure 34 shows the idealized situation where spoils become a man-made aquifer. The water table is near the surface of the ground prior to mining; upon abandonment, the excavated open pit and spoils fills with water to some depth, forming a lake and saturating some spoils. A useful water catchment has thus been made, albeit inadvertently. This situation has already been achieved at the Hidden Water Mine 5 mi. northeast of Monarch, Wyoming (Figure 4).

There are many variations in the idealized sequence shown in Figure 34. It is difficult to accurately assess the degree to which a useful water catchment area will be formed at specific mines because mines may not be able to accurately predict the number of years they will operate, and the ultimate size of their open pit. In this area coal mines are generally estimated to have life expectancies of 20 to 30 years. At a given rate of mining, for example 4 million tons per year, the volume of the open pit can be predicted. Economics will dictate the eventual break even point for the mines, however. As shown in Figure 34, the overburden gets thicker as mining progresses into the hillside. Currently a 3:1 to 5:1 overburden/coal ratio on a 50 ft. or greater coal bed is considered roughly break-even mining. Future energy needs will be dictated by uranium, oil, and other possible energy considerations, and will affect the economics of coal mining. Additionally, it is difficult to predict the future water level in abandoned mines because of limited data on the present position of the water table.

In this course of this research, it was found that the permeability of the scraper or truck-dumped spoils was approximately the same as natural sandstone or coal beds in the Tongue River Formation. Dragline-dumped spoils have permeabilities about twice as great as natural sandstone or coal beds. The permeability of clinker, however, is an order of magnitude greater than even the dragline-dumped spoils. Therefore it seems futile to elaborate on the possibility of recharging spoils when there are sizeable areas of highly permeable clinker all over the coal-producing area of the Powder River Basin (see, for instance, the areal extent of clinker mapped in Campbell County as shown in Breckenridge, et al. 1974). For these reasons, then, this section of this report is condensed to include only a brief description of the hydrologic conditins which may occur at the existing and proposed mining areas upon abandonment, and the economic, agricultural, or recreational use of water at these abandoned mines.

Wyodak Mine

The mine which has some of the best information on the present water table conditions is the Wyodak mine, 5 mi. east of Gillette. Figure 36 shows wells where static levels have been measured. Equipotential lines were drawn, and flow lines drawn perpendicular to the equipotential lines. It can be seen that ground water tends to move down the valley of Donkey Creek. The water table is approximately the same as the level of Donkey Creek which lies about 10 ft. above the top of the 85 ft. Wyodak coal bed.

The Wyodak Mine is exceptional in that it has a very thick coal bed and very little overburden (Appendix IV). For this reason the ultimate

open pit will probably be large but contain little spoils. Because the water table is high, the end product of mining will be for the most part a lake, containing submerged spoils on the bottom. Therefore it makes no sense to reclaim the spoils for agricultural purposes except for consideration during the actual time of mining.

Fifty years from now the residents of the Gillette area may want to use the lake for recreation. Therefore it would be advisable to move the effluent from the Gillette sewage plant to a point downstream on Donkey Creek; otherwise the lake would only be a sewage lagoon. If the unpolluted Donkey Creek is permitted to flow into the lake it would supply recharge waters, but sedimentation would lead to the ultimate filling in of the lake.

Belle Ayr Mine

Hydrogeologic conditions at the Belle Ayr Mine, 14 mi. south of Gillette, are described in research by the Wyoming Water Resources Research Institute and the U.S. Forest Service (Packer, 1975). Conditions generally are similar to the Wyodak Mine. The Belle Ayr Mine is along the flood plain of Caballo Creek (Figure 37). Although the overburden is thicker than Wyodak (Appendix IV), there may be insufficient spoils to fill in the excavation unless they are transported from areas of thicker overburden. According to Persse (1975), the mined area will be 70 ft. lower in elevation than the original ground. Thus a lake about 50 ft. deep would form over the spoils unless provisions are undertaken to prevent this. The lake could be recharged by Caballo Creek and could become a fine recreational area.

Bighorn Mine

The Bighorn Mine (Figure 11) is a large and complex area. Coal is

being mined beneath the flood plain of the Tongue River to the east of Acme, and is also being mined into a hillside southeast of Acme (Figure 32). Under the flood plain the open pit will largely fill with water, as is the case at the pump test site along Goose Creek described in Table 1 above. Under the hill, the open pit and contained spoils will ultimately be saturated to a varying but undetermined degree.

Decker Mine

The Decker Mine, 15 mi. northeast of Sheridan, (Figure 25 and 26) is one of the largest operating coal mines in the United States. It has been the site of hydrogeologic studies by the Montana Division of Mines and Geology (Van Voast, 1973, 1974).

The coal presently being mined northeast of the Tongue River is mostly at an elevation below the level of the Tongue River and the Tongue River Reservoir which backs water up to this point. Much of the water leakage into the mine on the east side is believed to be Tongue River water (R.A. Gjere, pers. comm.). The fact that the water table lies above the coal can be confirmed by inspection of Figure 35, which shows ground water seeping into the southwest side of the open pit.

On the basis of limited hydrogeologic data obtained from field inspection of the mine and topographic maps, it appears that the spoils will be largely saturated upon abandonment. This fact, combined with the relatively good permeability and porosity of dragline-dumped spoils will make the spoils productive for water wells. This aquifer can easily be recharged by surface canals from the Tongue River itself, which has a large discharge (Frickel and Shown, 1974). In doing so, however, the quality of the Tongue River water can be expected to deteriorate accordingly.

Because the availability of the Tongue River Reservoir which adjoins the Decker Mine, the question of whether it will ever be practical to artificially recharge the spoils during periods of high Tongue River discharges and later pump water out of the spoils during periods of drought can only be answered by future water resource economics.

Dave Johnston Mine

The Dave Johnston Mine, located 15 mi. north of Glenrock, is generally in a hilly area above the water table (see cross-sectional sketch in Appendix IV). Therefore these spoils are not likely to become saturated upon abandonment. The likelihood of artificially recharging the spoils with surface water seems remote because of the absence of streams in the area.

Colstrip

The Rosebud Mine, operated by Western Energy Co., and the Big Sky Mine, operated by Peabody Coal Co., are two of the larger mines in the Powder River Basin, and have been the site of extensive studies in reclamation (Hodder, et al, 1972) and limited studies in hydrology (Van Voast, 1974). Limitations on time prevent this research project from studying possible recharge sites at the Colstrip mines, but a preliminary reconnaisance of the area shows that there is the possibility of diverting Rosebud Creek from a position a few miles south into the Colstrip mining area.

Proposed Mines

The following is a brief description of the hydrogeology of several proposed mines. At most proposed mines hydrologic data is minimal.

Manv are located in remote areas for which $7\frac{1}{2}$ min. quadrangle topographic maps are not available. Data on stratigraphy of overburden based on mining company test holes is presented in Appendix IV. Data on the level of the water table in these test holes is generally not recorded by the mining companies. Therefore only the most cursory statements can be made at this time.

Carter Mining Company plans to develop the Rawhide Mine 10 mi. northeast of Gillette. Plans for the mining and reclamation are extensively treated in the Environmental Impact Statement (U.S. Dept. of Interior, 1974). Much of the mined area will be recharged by Little Rawhide Creek, and artificial lakes will be formed in the trough-like depressions of contoured spoils.

Atlantic Richfield Company (ARCO) plans to develop the Black Thunder Mine in T. 43 N., R. 70 W, about 40 mi. south-southeast of Gillette. According to the Environmental Impact Statement (U.S. Dept. of Interior, 1974, p. III-99), after mining is completed "the land will be returned to the same existing general landform, low rolling hills; two major streams will be reestablished in about their original streambeds; and water impoundments, depending on water quality and state water laws, can be created in the channels of North Prong and Little Thunder Creeks while maintaining normal downstream flow."

Kerr-McGee Coal Corporation also plans to develop the Jacobs Ranch mine in T. 43 N., R. 70 W, about 40 mi. south-southeast of Gillette. According to the Environmental Impact Statement (U.S. Dept. of Interior, 1974, p. v-105), "the overall altitude of the land could be reduced by 44 ft.; this could result in less runoff in low areas where ponding may occur." Hence the spoils will be saturated and submerged in places

by ground water and by the tributaries of the North Prong and Little Thunder Creek.

A recent draft environmental statement has been prepared on the Cordero Mine (U.S. Geological Survey, 1975). The Mine, owned by Sun Oil Co., will be in T. 47 N., R. 71 W, about 20 mi. south-southeast of Gillette. Plans call for the diversion of the Belle Fourche River during mining. After mining, much of the spoils will be submerged because (U.S. Dept. of Interior, 1975, p. III-2) "the average lowering of the land will be about 33 ft." and water table ponding will occur in topographic depressions in the spoils.

CONCLUSIONS

The information obtained in this research indicates that the coal strip mines in the Powder River Basin will inadvertantly produce numerous man-made aquifers. Where the overburden is predominately coarse-grained strata, and particularly where the overburden is stripped and dumped by dragline as opposed to scraper or trucks, the spoils will contain sufficient porosity and permeability which will be equivalent to or slightly greater than existing natural shallow sandstone aquifers. It is not known to what extent future natural compaction of the spoils may occur. In all likelihood the permeability and porosity would be less in spoils which have compacted over the years.

At some mines most of the spoils will ultimately become saturated with percolating ground water, such as the Decker, Bighorn, and Belle Ayr Mines. The Wyodak open pit will become largely a lake. In other mines streams can be diverted into the spoils to artificially recharge them to allow for the storage of water until the water can be withdrawn during the dry season.

Water quality will limit the use of water withdrawn from these spoils, however. Natural ground water has generally poor quality in the Powder River Basin. Water in spoils was found to be significantly more highly mineralized than natural ground water in terms of total dissolved solids, calcium, magnesium, and sulfate. Spoils water exceeds the recommended drinking water limits in these and other ions, and it is doubtful that the water could be used for long-term irrigation. Water collected in artificial lakes formed by the excavations or by depressions in spoils could be used for recreation (swimming or fishing) in artificial lakes, or used for livestock, or for fire prevention or industrial use.

To what extent the quality of water in spoils may improve centuries from now is impossible to predict, although lab studies by Vimmerstadt et al (1973) show it generally improve.

As a by-product of this research, clinker beds were found to have great potential for ground water recharge. Where saturated, the clinker yields water to wells ten times as great as spoils or existing sandstone aquifers. Future research in Powder River Basin hydrogeology should be directed to quantifying the extent and ground water potential of clinker beds.

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Figure 1. Index map of Powder River Basin. Landsat image #1300-17243, Band 5, taken on May 19, 1973 from an altitude of about 550 miles.

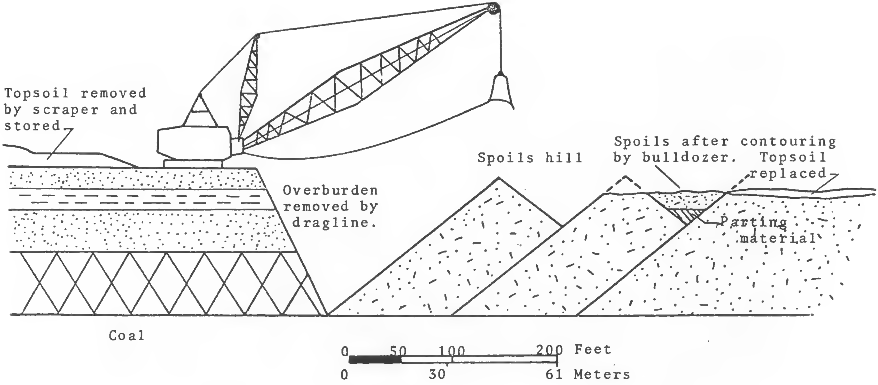


Figure 2. Cross-section of typical spoils emplacement by a dragline. (After Dept. of Interior, 1974, p. I-67.)

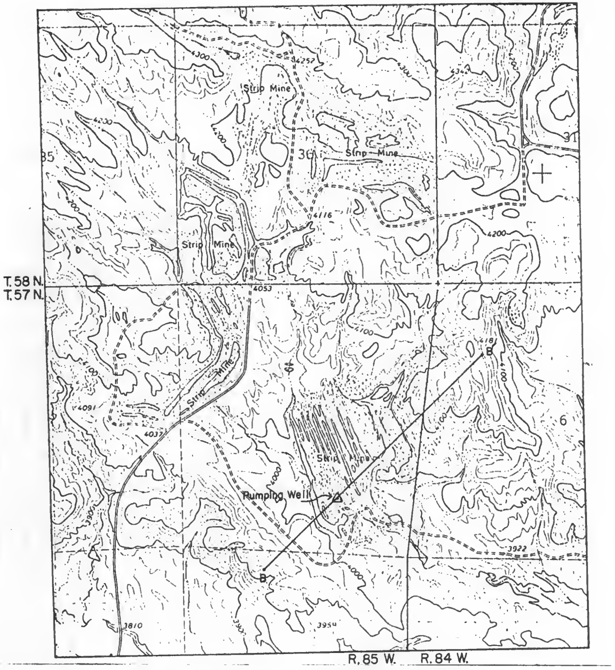
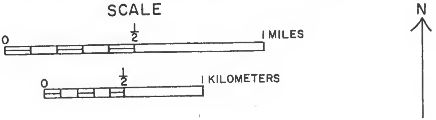


Figure 3. Topographic map of Hidden Water Creek coal mine area. From U.S. Geological Survey 7½ minute Monarch quadrangle. See Figure 4 for cross-section B-B'.



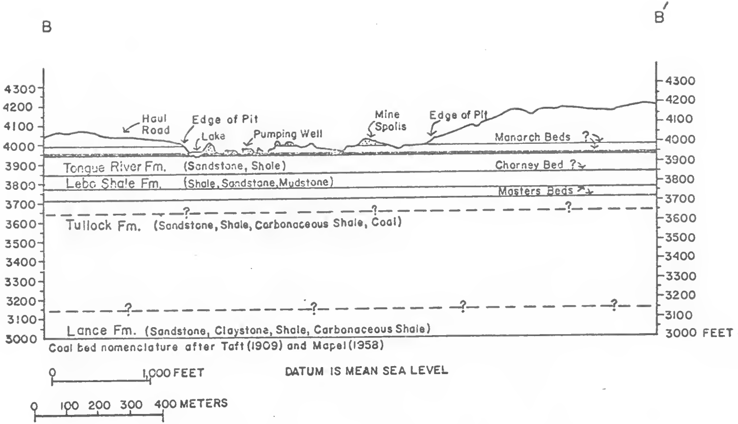


Figure 4. Geologic cross-section B-B' through the Hidden Water Creek coal mine pump test site showing the approximate stratigraphic relations of the coal beds within formations of the Fort Union Group. Location of section B-B' shown in Figure 3. Cross-section is drawn approximately parallel to the strike of the formation. Horizontal scale 2X map scale. Vertical 4X map scale.

Figure 5. Drilling observation well S. 85° W. no. 1, Hidden Water Creek mine.

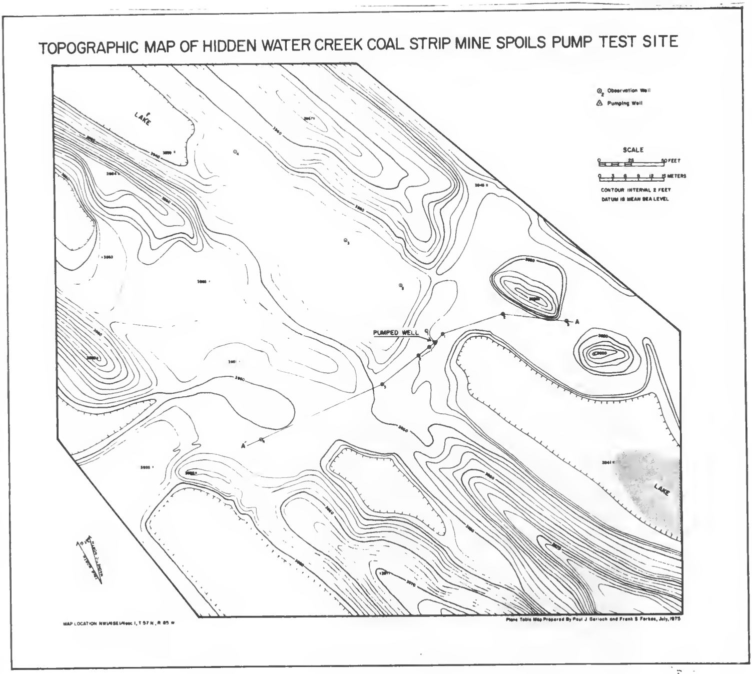


Figure 6. Detailed topographic map of Hidden Water Creek mine. See Figure 10 for cross-section A-A'.

Fig. 7 Topography of the Hidden Water Creek coal mine pump test site.

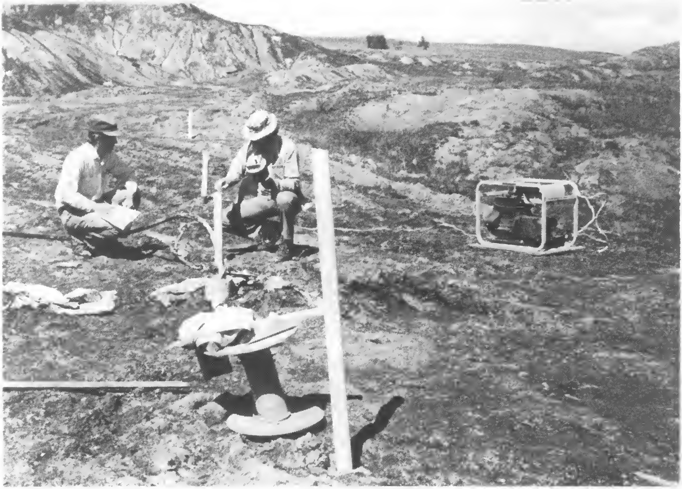


Fig. 8 Measuring the piezometric surface during the Hidden Water Creek coal mine pump test with a Soiltest electric water level indicator. A portable generator supplied electricity to power a submersible water pump.

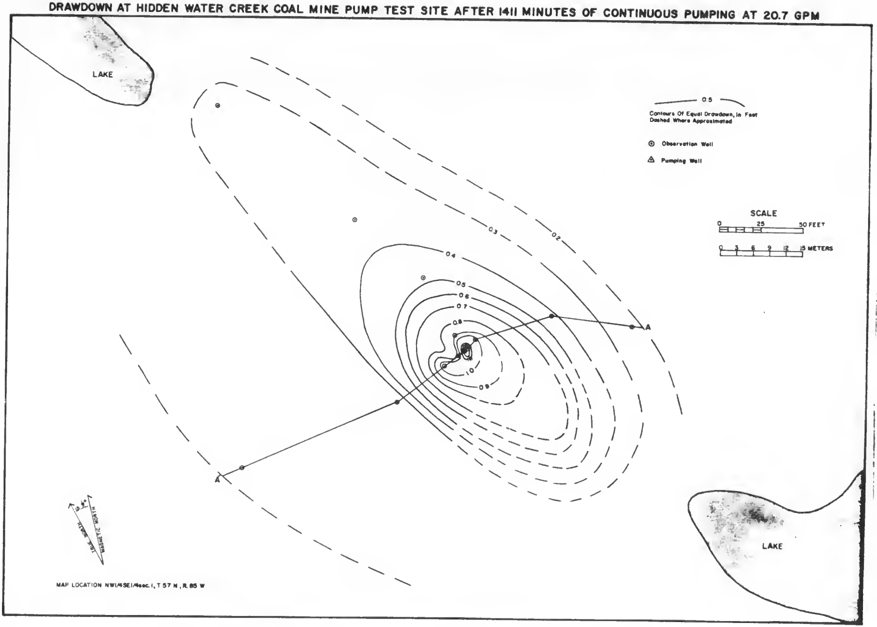


Figure 9. Drawdown after 1411 minutes of pumping at the Hidden Water pump test. See Figure 10 for location of cross-section A-A'.

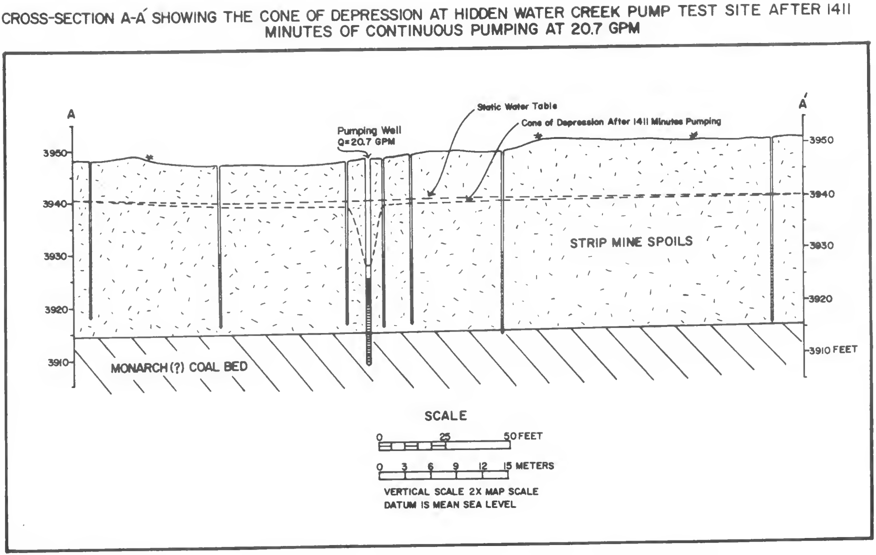


Figure 10. Cross-section at Hidden Water Creek pump test area. See Figure 9 for location of cross-section A-A'.

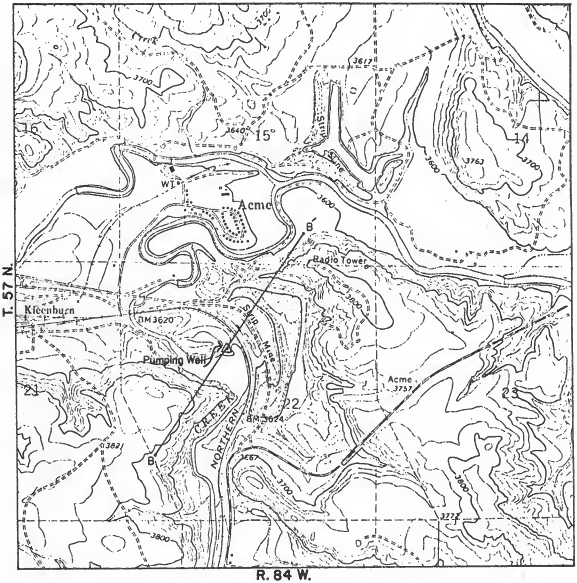
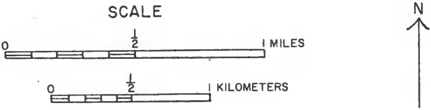


Figure 11. Topographic map of Bighorn mine. From U.S. Geological Survey $7\frac{1}{2}$ minute Acme quadrangle. See Figure 12 for cross-section B-B'.



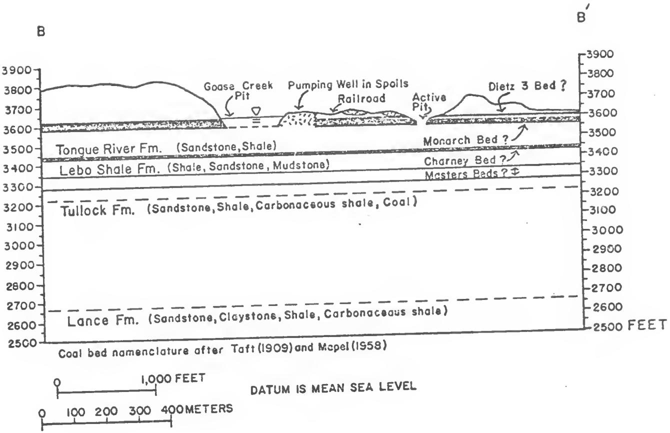


Figure 12. Geologic cross-section B-B' through the Bighorn coal mine pump test site showing the approximate stratigraphic relations of the coal beds within formations of the Fort Union Group. Location of section B-B' shown in Figure 11. Cross-section is drawn approximately parallel to the strike of the Tongue River Formation in this area.

Figure 13. Bighorn pump test site. Arrow points to pumping well. Goose Creek is in foreground.

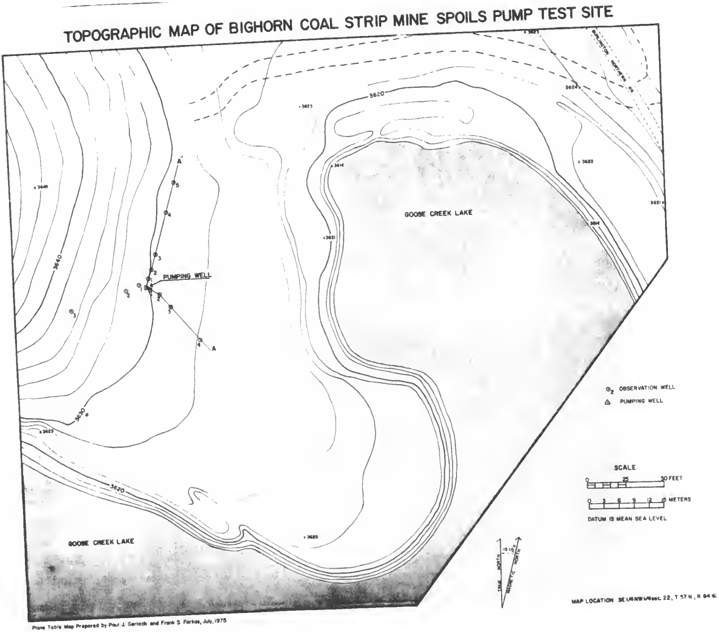


Figure 14. Detailed topographic map of Bighorn mine pump test area. Cross-section A-A' shown in Figure 16.

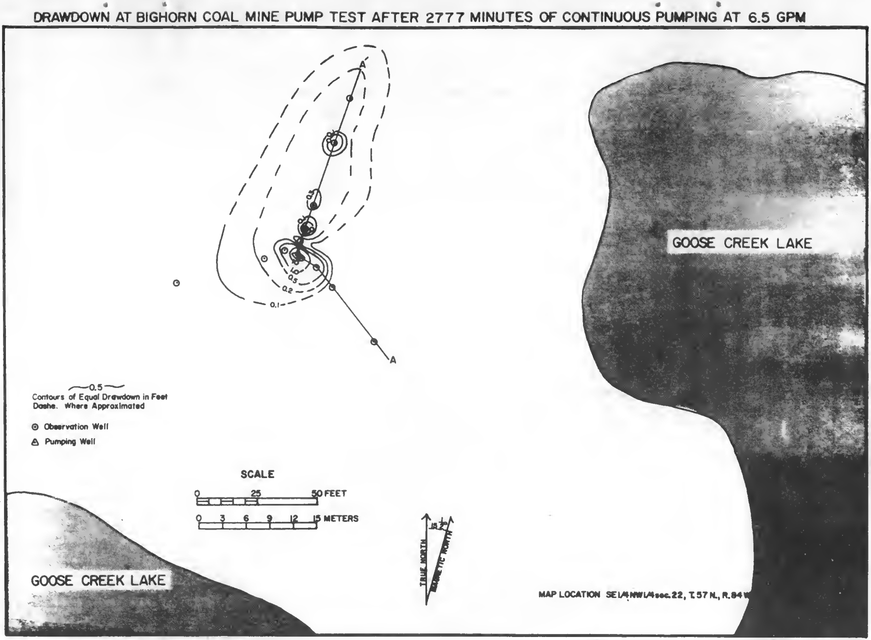


Figure 15. Map of drawdown after 2777 minutes of pumping at Bighorn pump test area. See Fig. 16 for cross-section A-A'.

CROSS SECTION A-A' SHOWING THE PRE-TEST WATER TABLE AT THE BIGHORN COAL MINE PUMP TEST AND THE PIEZOMETRIC SURFACE AFTER 2777 MINUTES CONTINUOUS PUMPING AT 6.5 GPM

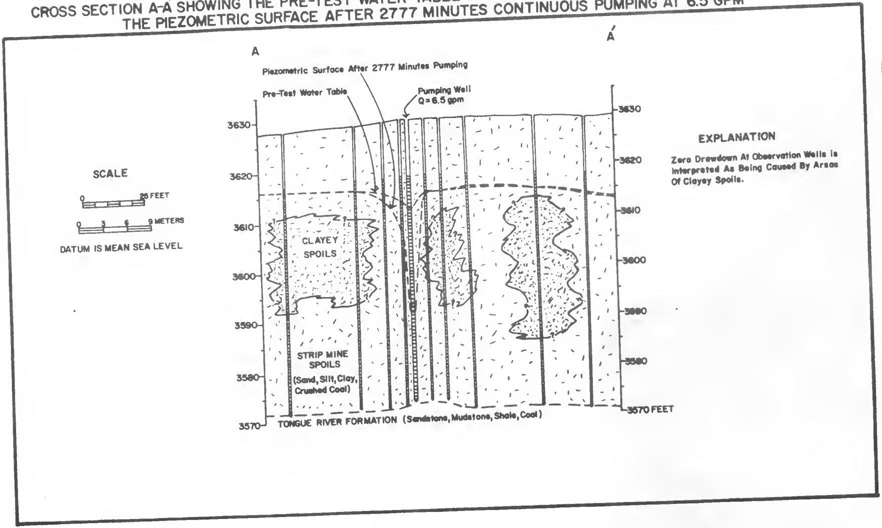


Figure 16. Cross-section at Bighorn pump test area. Location of section A-A; shown in Figure 14.

Figure 17. Infiltration tests at Hidden Water Creek mine (SE ¼ of Sec. 1, T. 57 N., R. 85 W.). Cylinders are spaced 15 ft. apart on the top of a 30 ft. high spoils pile.

Figure 18. Bighorn mine (SE $\frac{1}{4}$ of Sec. 15, T. 57 N., R. 84 W.). Spoils emplaced by dragline.

Figure 19. Belle Ayr mine (NW ¼ of Sec. 34, T. 48 N., R. 71 W.). Spoils emplaced by truck, then leveled by bulldozers and roadgraders.

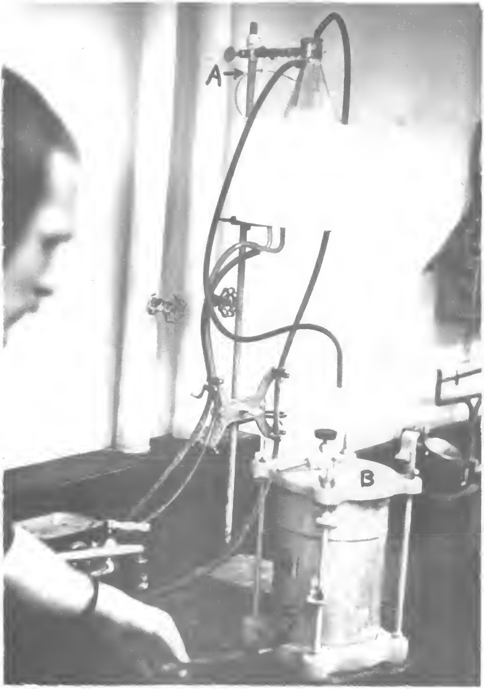
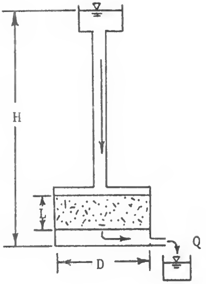


Figure 20. Soiltest model K-612 permeameter in operation. "A" indicates constant water head level. "B" indicates Soiltest permeameter containing spoils sample. "C" indicates outlet where discharge is collected.



Basic Formula

$$k = \frac{QL}{AH}$$

Parameters

$L = 7/12$ ft

$H = 34/12$ ft

$A = 0.1963\ ft^2$

K= Coefficient of permeability ($gal/day/ft^2$)

Q= Discharge (gal/day)

Conversion Units

500 ml= 0.1315 gal

1 day= 86400 sec

$$Q_{gal/day} = \frac{(0.1315)(86400)}{\text{Trial sec}}$$

$$k = \frac{(Q)(7/12)}{(0.1963)(34/12)} = 1.05(Q)\,gal/day/ft^2$$

Figure 21. Illustration of constant head permeameter. Parameters and conversion factors utilized in the calculation of permeabilities shown.

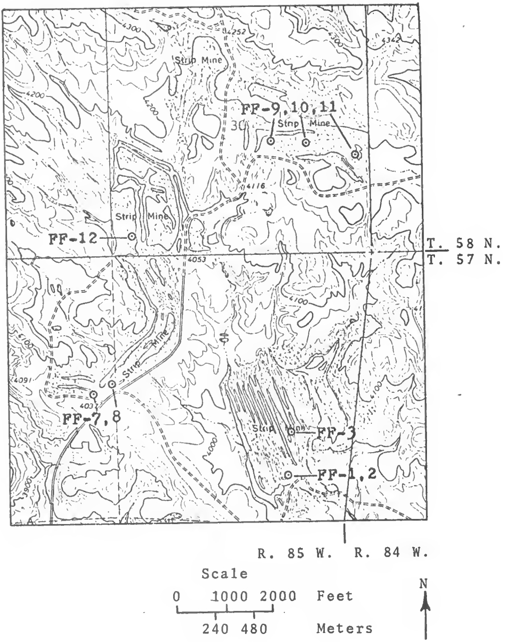


Figure 22. Topographic map of Hidden Water Creek Mine. Locations of nine infiltration test sites shown. (Base map from U.S. Geological Survey 7½ minute Monarch quadrangle, 1964).

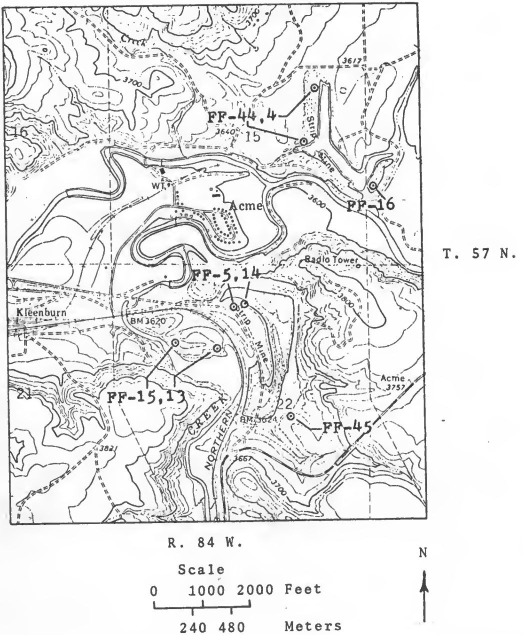


Figure 23. Topographic map of Bighorn Number One Mine. Location of eight infiltration test sites shown. (Base map from U.S. Geological Survey 7½ minute Acme quadrangle, 1968).

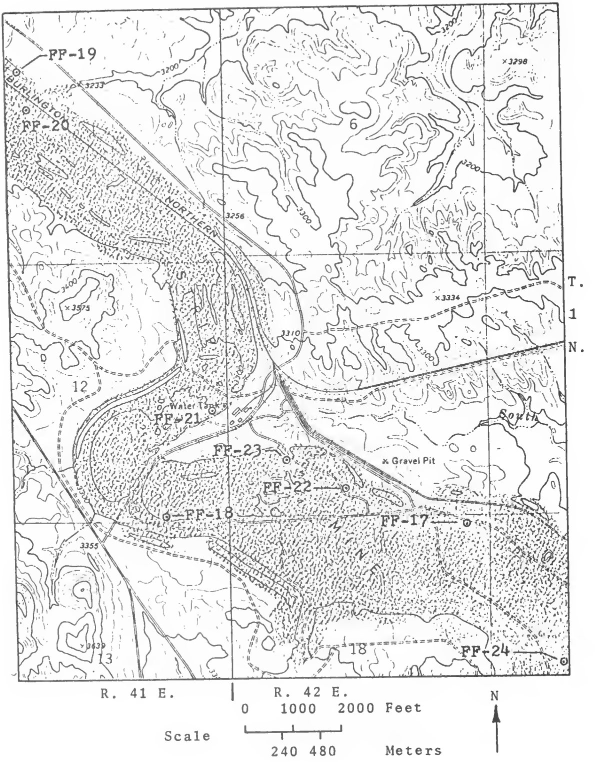


Figure 24. Topographic map of Rosebud Mine. Locations of eight infiltration test sites. (Base map from U.S. Geological Survey 7½ Colstrip SE quadrangle, 1971).

Figure 25. Decker mine (SW¼sec. 16, T. 9 S., R. 40 E.). "A" shows spoils which have been contoured but no topsoil added. Vegetated spoils in area "B" have topsoil added. Area "C" shows large uncontoured spoils hill as left by dragline. Current mining operations are shown in area "D". Area "E" shows undisturbed overburden.

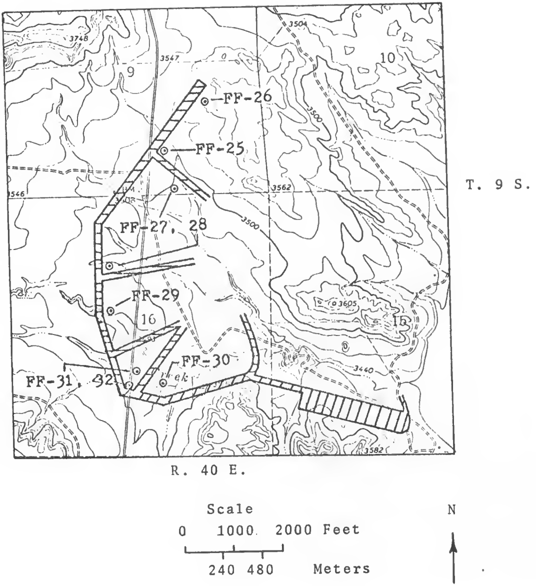


Figure 26. Hachured area shows approximate outline of 1975 working pit with access roads, Decker Mine. Spoils areas indicated by eight infiltration test sites shown. (Base map from U.S. Geological Survey $7\frac{1}{2}$ minute Decker quadrangle, 1967).

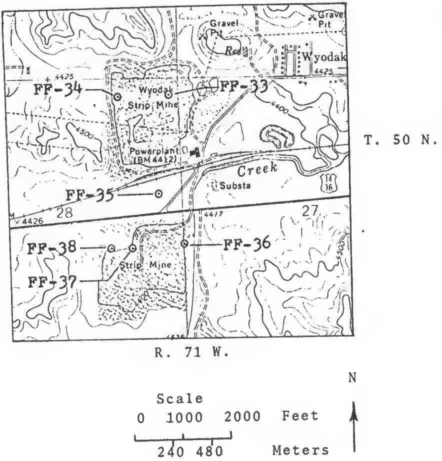


Figure 27. Topographic map of Wyodak Mine. Locations of six infiltration test sites shown. (Base map from U.S. Geological Survey 7½ minute Gillette East quadrangle, 1971.)

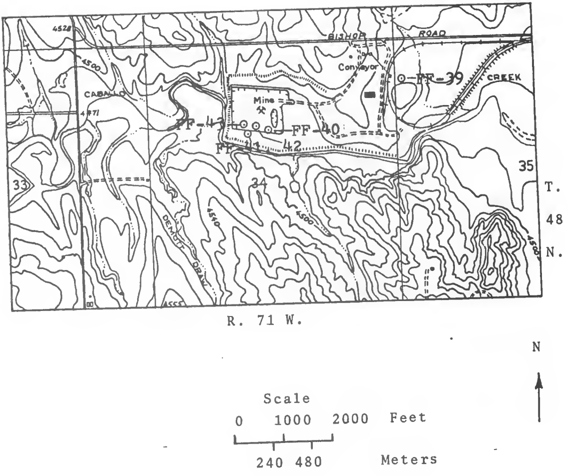


Figure 28. Topographic map of Belle Ayr mine. Locations of five infiltration test sites shown. (Base map compiled from U.S. Geological Survey 7½ minute Gap SW and Saddle Horse Butte quadrangles, 1971.)

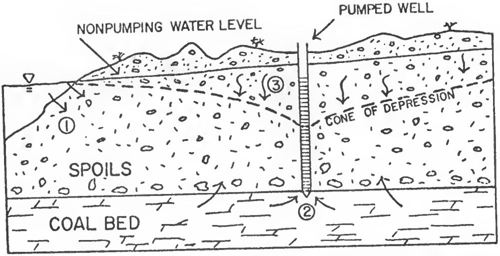
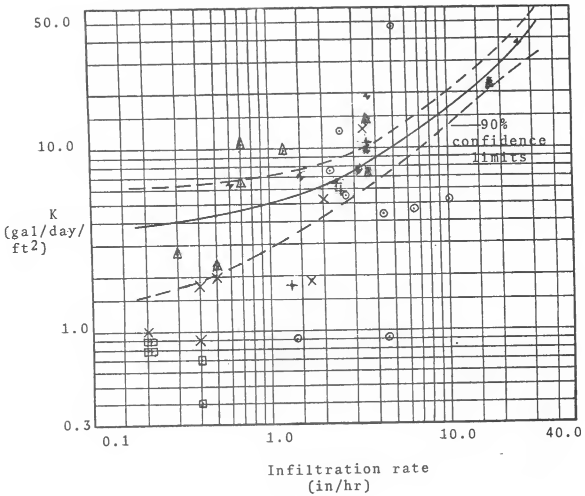


Figure 29. Diagrammatic representation showing the three idealized ways leaky artesian time-drawdown data curves may be generated while pumping a water table aquifer: 1) Induced infiltration of water from a body of surface water, 2) Recharge from an underlying aquifer, 3) Delayed gravity drainage of fine-grained sediments.



Statistical Data:

Equation of line: $y = 3.685 + 1.301x$

$r = +0.643$

$r^2 = 0.413$

⊙ Hidden Water Creek Mine
△ Big Horn Mine
✕ Rosebud Mine
⊡ Decker Mine
Wyodak Mine
+ Belle Ayr Mine

Figure 30. Graph of laboratory permeability versus infiltration rate for all six mines investigated.

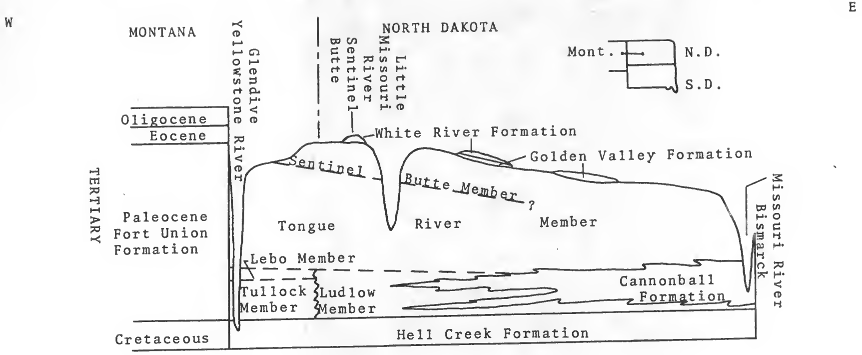


Figure 31. Idealized stratigraphic section of Upper Cretaceous and Tertiary formations between Glendive, Montana and Bismark, North Dakota. Not to scale. (After the Tertiary Committee, 1954, p. 12.)

Figure 32. Main pit of Bighorn coal mine. Dietz #3 (?) and Monarch (?) coal beds converge to produce a single workable coal bed nearly 50 ft. thick. Arrow in photo points to the approximate location of the measured section listed in the Appendix.

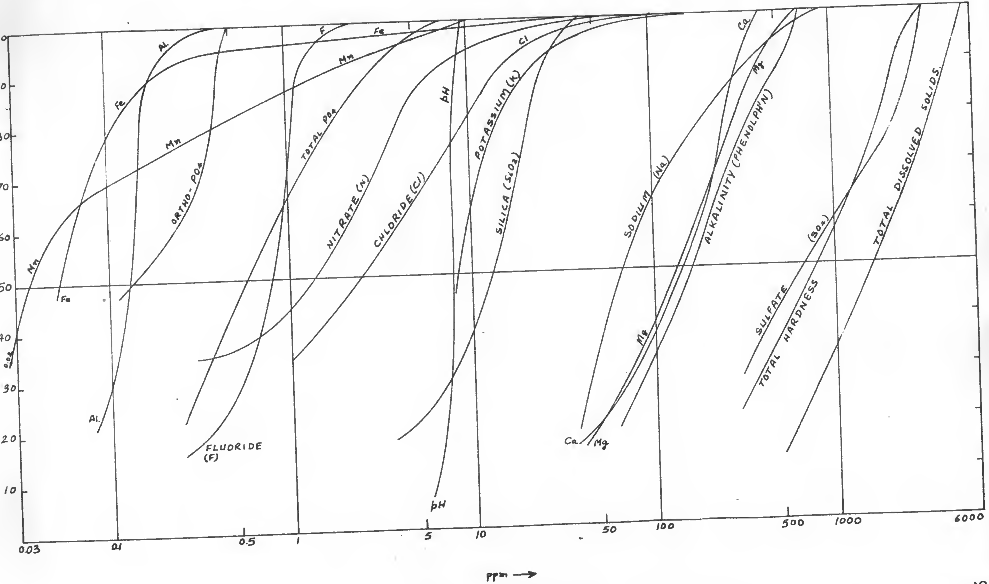


Figure 33. Cumulative frequency curves for water quality data.

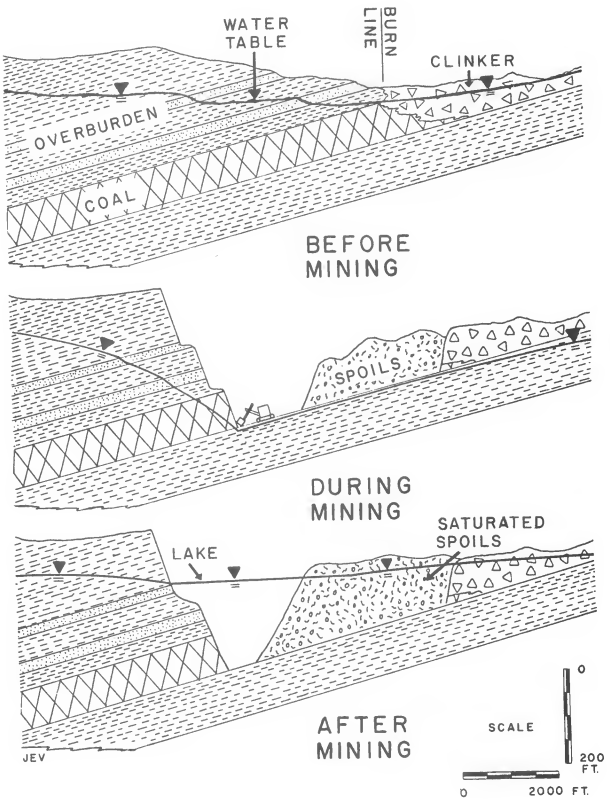


Figure 34. Idealized sketch showing three stages of development of a coal mine.

Figure 35. Working face of the Decker Mine, Montana. Arrow locates ground water seeps (water sample OW-11) just over the Dietz #1 coal bed. Three white areas on coal in foreground are fires caused by spontaneous combustion.

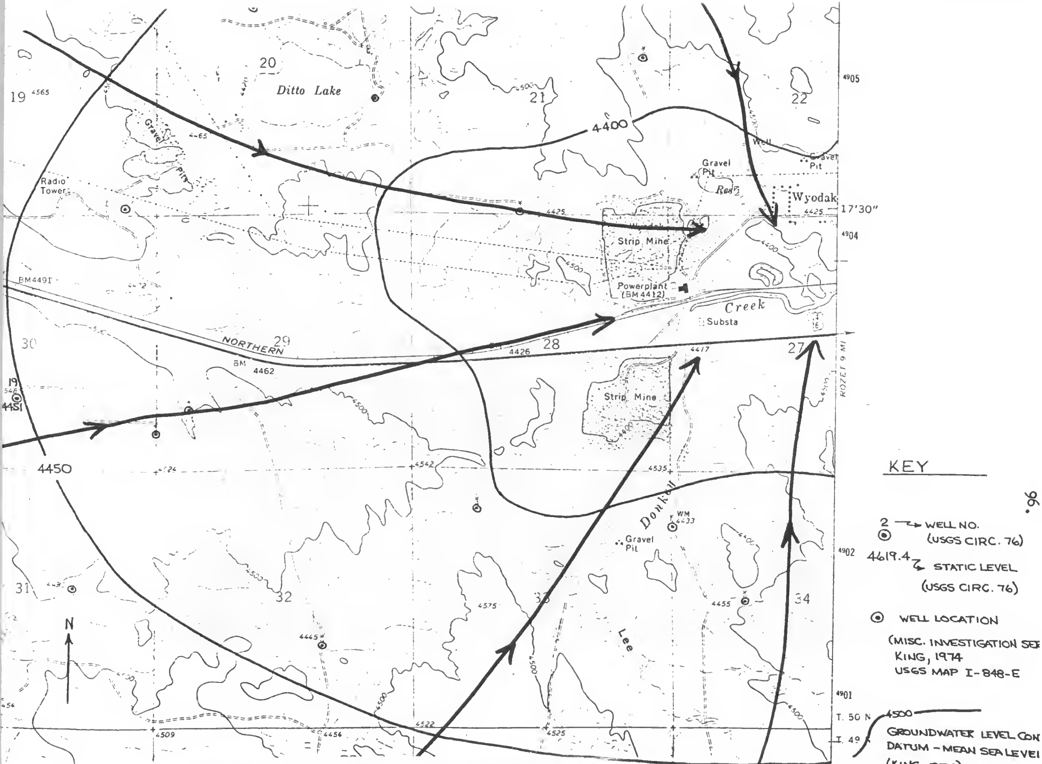


Figure 36. Ground water flow net at Wyodak mine.

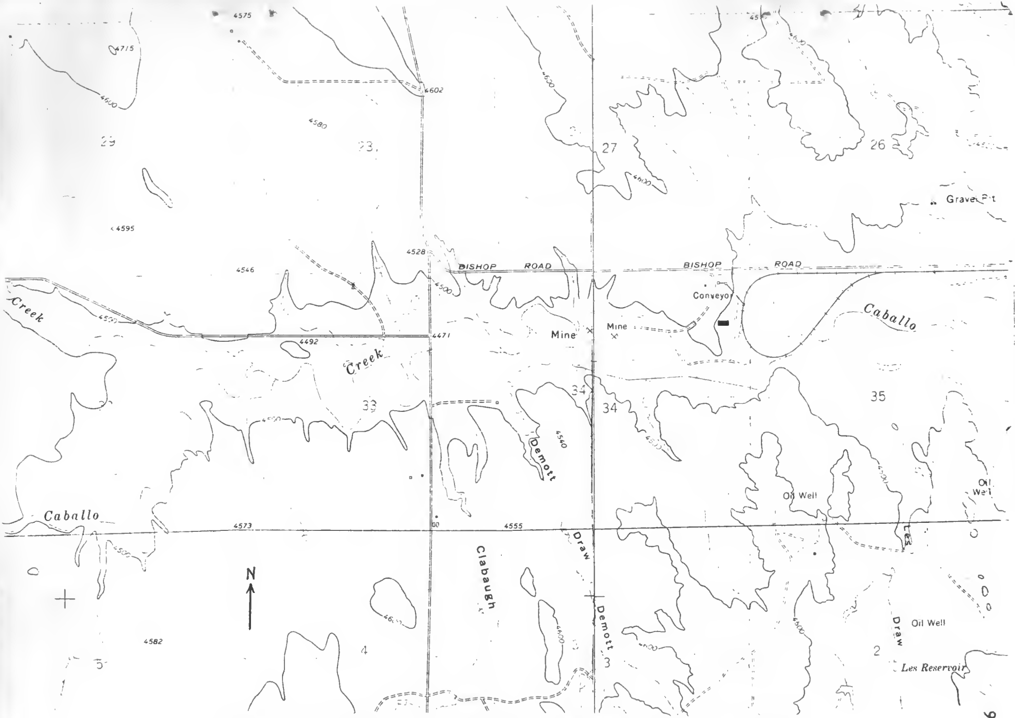


Figure 37. Topographic map of Belle Ayr mine area. From U.S. Geological Survev 7½ minute quadrangle maps, The Gap SW and Saddle Horse Butte, 1971.

Table 1. Summary Calculations for Transmissivity (T), Permeability (K), Storage (S), Thickness of Saturated Spoils (B), and Leaky Function (r/B) for the Hidden Water Creek Coal Mine Spoils Pump Test.

Time-Drawdown Plots:

Obs. Well	T(gpd/ft)	K(gpd/ft^2)	S	B(ft)	r/B	Comments
S.85°W.#1	10,310	430	0.035	33.0	0.20	good curve
S.85°W.#2	9,120	370	0.062	24.5	0.15	good curve
S.85°W.#3	5,600	210	0.496	26.5	——	fair curve
S.85°W.#4	6,680	250	0.039	26.5	——	fair curve
N.20°W.#1	9,880	400	0.125	24.5	0.25	good curve
N.20°W.#2	7,190	300	0.131	24.0	0.50	good curve
N.20°W.#3	9,970	440	0.022	22.5	0.50	good curve
N.20°W.#4	6,540	320	0.006	20.5	1.00	fair curve
E.22°S.#1	15,300	660	0.077	23.0	——	good curve
E.22°S.#2	6,080	260	0.270	23.5	——	fair curve
E.22°S.#3	4,160	190	0.151	22.0	——	fair curve
Average	8,257	348	0.128	24.5	0.24	

Distance-Drawdown Plots:

Obs. Wells	T(gpd/ft)	S	Comments
Wells S.85°W.1-4	14,010	0.137	good curve
Wells E.22°S.1-3	14,380	0.112	good curve
Wells N.20°W.1-4	——	——	no curve
Average	13,850	0.212	

Table 2. Water quality at Hidden Water Creek pump test area. 1. strip mine pond southeast of Hidden Water Creek mine pumping well, and water quality of pumping well discharge after 2. 1.95 hours pumping, and after 3. 26.42 hours pumping. Analysis determined by the Engineering and Experiment Station, South Dakota School of Mines and Technology.

Substance	Concentration, mg/l		
	1	2	3
Total Dissolved Solids	1826	5210	5906
Volatile Dissolved Solids	310	618	1366
Total Suspended Solids	13	71	105
Total Hardness	996	3392	3434
Carbonate Hardness	184	166	188
Non-Carbonate Hardness	812	3226	3246
pH	(8.2)	(5.8)	(5.9)
Alkalinity (Met. Orange)	184	166	188
Turbidity (J.U.)	(20)	(400)	(400)
Spec-Conductance	(1900)	(4100)	(4400)
Calcium (Ca)	115	392	334
Magnesium (Mg)	172	586	753
Sodium (Na)	88	175	100
Potassium (K)	25	15	20
Iron (Fe)	0.02	21	30
Manganese (Mn)	0.02	10	7
Chloride (Cl)	1.5	1.5	1.0
Sulfate (SO_4)	860	3134	3133
Silica (SiO_2)	8.3	29	33
Nitrate (N)	0.06	0.11	0.06
Orthophosphate (PO_4)	0.1	0.1	0.1
Total Phosphate (PO_4)	3.1	7.0	5.8

Table 3. Water quality at Bighorn pump test area. 1. Goose Creek Pond at the Bighorn coal mine pump test site, 2. groundwater seep at the south end of main pit of the Bighorn coal mine, 3. pumping well discharge of Bighorn mine pump test after 1.10 hours pumping, and 4. pumping well discharge after 32.80 hours pumping. Analyses determined by the Engieering and Mining Experiment Station, South Dakota School of Mines and Technology.

Substance	Concentration, mg/l			
	1	2	3	4
Total Dissolved Solids	222	4096	2548	2372
Volatile Dissolved Solids	28	90	244	314
Total Suspended Solids	52	8	617	54
Total Hardness	141	982	1647	1221
Carbonate Hardness	104	566	290	254
Non-Carbonate Hardness	37	416	1357	967
pH	(9.10)	(7.10)	(8.6)	(8.7)
Alkalinity (Phenolph'n)	6	——	14	6
Alkalinity (Met. Orange)	104	566	290	254
Turbidity (J.U.)	——	4	——	——
Spec. Conductance	(210)	(4700)	(1820)	(1780)
Calcium (Ca)	31	182	353	188
Magnesium (Mg)	16	128	186	183
Sodium (Na)	8	850	97	85
Potassium (K)	1	33	30	26
Iron (Fe)	0.08	0.06	0.10	0.06
Manganese (Mn)	0.05	0.05	0.63	0.63
Chloride (Cl)	2.5	2	1.5	2
Sulfate (SO_4)	58	2345	1020	1262
Silica (SiO_2)	8.5	19.6	25	25
Nitrate (N)	0.26	1.3	3.9	3.91
Orthophosphate (PO_4)	0.32	0.3	0.25	0.17
Total Phosphate (PO_4)	0.40	0.4	0.64	0.48

Table 4. Infiltration data summary for all mines investigated in the Powder River Basin.

Mine	Test Site*	Infiltration Rate (in/hr)	Laboratory Permeability (gal/day/ft^2)	Field Moisture Content (%)	Field Density (lb/ft^3)
Hidden Water Creek Mine	FF-1	10.0	5.2	10.3	81.3
	FF-2	2.7	5.5	10.3	81.3
	FF-3	6.5	4.6	7.3	102.5
	FF-7	5.0	48.0	10.7	73.7
	FF-8	4.4	4.4	5.8	83.6
	FF-9	2.2	7.6	11.3	110.1
	FF-10	4.6	0.9	15.2	97.3
	FF-11	1.4	0.9	8.1	92.4
	FF-12	2.5	12.6	12.9	106.8
Big Horn Mine	FF-4	17.6	22.8	12.2	93.2
	FF-5	0.7	6.6	10.2	95.0
	FF-13	1.2	9.9	4.4	104.6
	FF-14	0.5	2.3	5.6	106.8
	FF-15	3.5	14.6	9.7	88.5
	FF-16	0.7	10.8	6.3	84.2
	FF-44	3.6	7.3	8.6	105.6
	FF-45	0.3	2.7	9.3	108.3
Rosebud Mine	FF-17	2.0	5.1	1.3	86.8
	FF-18	2.0	57.6	6.1	76.5
	FF-19	0.5	2.0	2.0	115.3
	FF-20	0.4	0.9	1.8	111.5
	FF-21	1.7	1.9	1.3	112.2
	FF-22	0.2	1.0	2.0	95.3
	FF-23	0.4	1.8	2.9	109.3
	FF-24	3.4	13.0	0.7	104.5
Decker Mine	FF-25	0.2	0.8	1.6	126.7
	FF-26	0.4	0.7	2.0	121.1
	FF-27	37.5	0.9	3.4	102.7
	FF-28	10.0	1.5	4.8	96.6
	FF-29	0.2	0.9	3.2	104.6
	FF-30	0.2	0.9	2.0	108.0
	FF-31	0.4	0.4	3.6	115.4
	FF-32	0.2	0.8	2.9	128.7
Wyodak Mine	FF-33	3.5	9.5	10.4	101.6
	FF-34	0.6	6.6	3.9	124.8
	FF-35	25.7	38.0	5.5	96.2
	FF-36	3.6	19.8	5.1	81.3
	FF-37	1.5	7.1	2.5	114.4
	FF-38	3.2	7.7	3.9	111.2
Belle Ayr Mine	FF-39	1.3	1.8	3.6	122.8
	FF-40	2.4	6.6	3.7	88.5
	FF-41	2.5	39.7	6.8	89.0
	FF-42	2.5	5.9	5.4	98.1
	FF-43	3.5	10.6	4.8	98.5

* Locations of test sites are shown on topographic maps included in the detailed description of coal strip mines studied section, later in this paper.

	Dragline Dumped Spoils				Scraper & Truck Spoils			
	Hidden Water	Rosebud	Decker	ave.	Bighorn	Wyodak	Belle Ayr	ave.
Lab Perm. (gpd/ft^2)	10.0	10.4	0.9	10.1	9.6	14.8	12.9	12.4
inf. rate 4.4 (in/hr)	4.4	1.3	0.3	3.0	3.5	6.4	12.9	7.6

Table 5. Summary of infiltration and lab permeability for six mines.

EXISTING MINES	SILT-STONE	CLAY, MUD, SHALE	SAND, SAND-STONE	MISCEL-LANEOUS	PERMEABILITY FACTOR ($\geq$ss/$\leq$sh)
Belle Ayr (Amax Coal Co.)					
Section A	4'	35'	91'		
Section B		75'	61'		1.33
Bighorn (Peter Kiewit and Sons)		97.12'	2'	sandstone float--18'	.21
Decker (Peter Kiewit and Sons)					
Section A	9.9'	8.1'	46.7'	26' lost	
Section B	64.6'	99.9'	5'		.28
Hidden Water Creek		35.5'	14'	2' sandstone and shale; 3" coal	.39
Dave Johnston (Pacific Power and Light)			359'	6'silty coal	>359
Rosebud (Western Energy)		20'	300'		15
Welch (Best Coal Co.)		24.75'	9'	1.75 sub-bituminous coal	.36
Wyodak (Black Hills Power and Light)					
Section 1, North Pit		47.25'	13.5'		
Section 1, South Pit		27'		2.5' clayey soil	
Section 2, South Pit		29.33'		.5'soil	.12

Table 6. Overburden lithology for mines in Powder River Basin.

PROPOSED MINES	SILT-STONE	CLAY, MUD, SHALE	SAND, SAND-STONE	MISCEL-LANEOUS	PERMEABILITY FACTOR
Amax Coal Co., Amax North Mine (sections from 2.5 mi. and 1.5 mi. SW of the lease area)	18'	327'	25'	10' soil 15' sand, silt, and clay 5' coal and shale	.08
Atlantic-Richfield Co., Black Thunder Mine		41.67'	2.15'	14' soil; 19.75' sand, silt, and clay: 25.85' sands and silts	.29
Carter Oil Co., North Rawhide Mine (sections from 1 mi. S and 2.5 mi. SW of the lease area)		76'	129'	12' soil	1.69
Kerr-McGee Co., Jacobs Ranch Mine		52.5'	59.0'		1.12
Peabody Coal Co.,		65'	75'	10' soil	1.15
Sun Oil Co. Cordero Mine		145'	25'	10' soil	.17

Table 6 (cont.)

SAMPLE

Substance (MG/L)	Maximum Recommended drinking water limits g	OW-1	OW-2	OW-3	OW-4	OW-5	OW-6	OW-7	OW-8	OW-9	OW-10
Total Dissolved Solids	1500	5510[y]	1012	852	2212[x]	1222	1626[x]	2610[z]	2016[x]	1176	4096[x]
Volatile Dissolved Solids		676	14?	184	262	108	288	452	330	152	90
Total Suspended Solids		5	10	9	2	5	14	11	20	14	8
Volatile Suspended Solids			10								
Total Hardness		2554	580	709	1527	727	948	1488	1027	760	982
Carbonate Hardness		99	195	295	188	158	448	511	681	107	566
Non-Carbonate Hardness		2455	394	414	1161	571	499	1152	346	593	418
pH		7.01	8.0	7.84	7.82	7.94	7.46	7.48	7.07	8.00	7.10
Alkalinity Phenolphthalein			0							6	
Alkalinity Meth. Orange		99	195	295	188	158	446	311	681	107	566
Turbidity (J.U.)		<4	4	26	4	4	16	10	22	12	<4
Spec. Conductance		4100	1000	1500	2200	1350	1900	2750	2600	1500	4700
Calcium (Ca)	200	431[x]	140	156	519[x]	182	230[x]	516[x]	234[x]	82	182
Magnesium (Mg)	125	360[x]	55	78	129[x]	66	90	194[z]	106	121	129[x]
Sodium (Na)	200 b	190	50	22	111	29	130	178	358[y]	93	860[y]
Potassium (K)	c	255	24	6	40	31	18	18	17	16	33
Iron (Fe)	1.0	0.13	0.08	0.18	0.15	0.13	0.13	0.16	0.34	0.10	0.06
Manganese (Mn)	.05	0.51[x]	0.05	0.30[y]	0.40[y]	0.05	0.09[x]	<0.06	0.56[z]	<0.05	<0.06
Aluminum (Al)	c	0.10		0.10	0.18	0.18	0.08	0.19	0.09	0.68	0.42
Chloride (Cl)	250	17	4.8	1	8	2	1	103	0.8	11	2
Sulfate (SO4)	250	3085[z]	500[x]	488[x]	1370[y]	639[x]	816[y]	1366[y]	968[y]	710[x]	2348[y]
Silica (SiO2)	c	44	17	18	28	51	21	22	22.3	2.4	19.6
Nitrate (N)	20	4.4	0.10	2.2	3.7	4.4	8.2	8.2	2.0	0.7	1.2
Orthophosphate (PO4)	c	0.1	<0.1	0.1	0.5	0.6	0.5	0.3	0.1	0.4	0.5
Total Phosphate (PO4)	c	1.3	0.1	0.5	0.9	1.6	1.6	0.6	1.3	0.4	0.4
Fluoride (F)	1.6	1.31		1.00	1.31	1.26	1.16	1.36	1.06	1.20	1.20
TRACE ELEMENTS											
Antimony	.08										nt
Arsenic	.05 a										<0.01
Barium	1.00 a										< 0.8
Boron	20. d										1.3
Bromide	e										-f-
Cadmium	.01 e										.017[x]
Chromium (Hexavalent)	.05 a										<.008
Cobalt	e										.026
Copper	1.0										.006
Cyanide	0.2 a										nt
Germanium	e										-f-
Iodide	e										-f-
Lead	.08 a										<.001
Lithium	e										.43
Mercury (Dissolved)	.005 a										nt
Molybdenum	e										.04
Selenium	.01 a										<.01
Silver	.05 a										nt
Strontium	e										1.7
Uranium	e										-f-
Vanadium	e										.04
Zinc	5.0										.016

Substance (MG/L)	OW-11	OW-12	OW-13	OW-14	OW-15	OW-16	OW-17	OW-18	OW-19	OW-20
Total Dissolved Solids	4732[y]	1000	2994[x]	2954[x]	3162[y]	1168	4994[y]	1810[x]	2008[x]	1594[x]
Volatile Dissolved Solids	330		490	558	908	454	676	364	442	270
Total Suspended Solids	2	6								
Volatile Suspended Solids										
Total Hardness	1473	536	2063	1600	3048	627	2982	909	1400	900
Carbonate Hardness	438	178	644	178	188	154	149	271	533	
Non-Carbonate Hardness	1036	358	1419	1633	2857	473	2833	638	567	
pH	6.56	8.64	7.75	8.28	7.85	8.03	7.92	7.72	7.77	8.37
Alkalinity Phenolphthalein	14	10								6
Alkalinity Meth. Orange	438	178	644	178	188	154	149	271	533	82
Turbidity (J.U.)	10	4								
Spec. Conductance	2000	1300	2100	2700	5200	1300	3500	1600	2150	1000
Calcium (Ca)	141	82	536[x]	168	364[x]	92	261[x]	158	152	126
Magnesium (Mg)	272[x]	99	298[x]	339[x]	820[y]	96	596[y]	137[x]	248[x]	142[x]
Sodium (Na)	900[y]	96	74	68	170	44	120	91	110	74
Potassium (K)	21	17	11	14	17	7	20	7	8	13
Iron (Fe)	0.08	0.03	0.06	0.12	0.08	0.08	0.08	0.08	0.1	0.12
Manganese (Mn)	<0.06	<0.06	<0.05	<0.08	<0.06	<0.05	<0.06	<0.05	<0.08	<0.06
Aluminum (Al)	0.09	0.15	0.11	0.12	0.15	0.13	0.12	0.11	0.11	0.16
Chloride (Cl)	1	10	1	14	13	4	11	2	1	9
Sulfate (SO4)	2309[z]	540[x]	1700[y]	1600[y]	3100[z]	588[x]	2750[x]	840[y]	1050[y]	880[y]
Silica (SiO2)	0.1	2.4	21	11	10	18	9	18	15	8
Nitrate (N)	0.6	1.0	8.2	<0.10	<0.1	63[y]	<0.1	21[x]	2	<0.1
Orthophosphate (PO4)	0.4	0.4	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Total Phosphate (PO4)	2.7	0.8	1.8	0.7	0.9	0.8	0.5	0.7	0.6	0.3
Fluoride (F)	2.93[x]	0.82	0.9	0.5	0.95	0.05	0.88	0.6	0.68	0.2
TRACE ELEMENTS										
Antimony	nt									
Arsenic	<0.01									
Barium	< 0.5									
Boron	1.7									
Bromide	-f-									
Cadmium	.014[x]									
Chromium (Hexavalent)	<.006									
Cobalt	.032									
Copper	.005									
Cyanide	nt									
Germanium	-f-									
Iodide	-f-									
Lead	<.01									
Lithium	.36									
Mercury (Dissolved)	nt									
Molybdenum	.019									
Selenium	<.91									
Silver	nt									
Strontium	1.7									
Uranium	-f-									
Vanadium	<.01									
Zinc	.009									

Substance (MG/L)	OW-21	OW-22	OW-23	OW-24	OW-25	OW-26	OW-27	OW-28	OW-29	OW-30	OW-31	OW-32
Total Dissolved Solids	458	4318[z]	2864[x]	5810[y]	8906[y]	1838[x]	222	1846[x]	2372[x]	1224	1353	604
Volatile Dissolved Solids	36	330	538	618	1586	310	28	344	314	66	213	70
Total Suspended Solids	1.4	2.0	34	71	106	12	52	617	54	19	63	
Volatile Suspended Solids												
Total Hardness	300	1887	1887	2308	3434	994	141	1947	1231	56	300	296
Carbonate Hardness	182	306	30	166	168	194	104	290	254	56	300	82
Non-Carbonate Hardness	118	1581	1857	3228	3246	812	37	1357	967	0	0	216
pH	8.8	8.2	7.8	8.8	5.8	6.2	9.1	6.8	5.7	8.1	8.8	7.30
Alkalinity Phenolphthalein	66	42					6	14	8	50	34	
Alkalinity Meth. Orange	182	306	30	166	188	194	104	290	254	674	492	82
Turbidity (J.U.)				~400	~400	30						
Spec. Conductance	500	3200	2900	4100	4400	1900	210	1820	1780	1400	1300	900
Calcium (Ca)	67	229[x]	297[x]	392[x]	334[x]	115	31	353[x]	188	6.8	98	65
Magnesium (Mg)	33	322[x]	279[x]	886[y]	783[y]	172	16	186	183	7.8	35	32
Sodium (Na)	30	479[y]	250[y]	175	100	68	8	97	95	425[x]	340[x]	53
Potassium (K)	4	30	18	16	20	25	1	30	26	6	0	8
Iron (Fe)	0.6	6.6	0.02	21[z]	30[z]	< 0.02	0.06	0.10	0.06	0.24	0.10	9.13
Manganese (Mn)	<0.05	0.06	3.9[z]	10[z]	7[z]	0.02	0.05	0.63[z]	0.63[z]	<0.05	<0.06	0.13[x]
Aluminum (Al)												
Chloride (Cl)	0	2.0	7.0	1.8	1.0	1.5	2.5	1.6	2.0	2.0	1.0	19
Sulfate (SO4)	97	2636[z]	3470[y]	3134[z]	3133[z]	860[y]	58	1020[y]	1262[y]	62	585[x]	325[x]
Silica (SiO2)	14	30	2.0	30	33	6.5	6.6	25	25	6.8	8.6	5.5
Nitrate (N)	1.90	0.54	2.1	0.11	0.06	0.04	0.26	6.0	3.91	1.74	0.30	1.8
Orthophosphate (PO4)	0.10	0.42	0.16	<0.1	<0.1	<0.1	9.33	0.25	0.17	0.40	0.25	6.5
Total Phosphate (PO4)	3.3	3.2	0.71	7.0	6.8	3.1	0.40	0.64	0.48	1.2	1.5	0.8
Fluoride (F)												

Notes

a - Mandatory Limits of U. S. P. H. S. (1962)
b - Irrigation water should have 300 ppm sodium.
c - Not harmful to humans dissolved water.
d - Irrigation water should have 3 ppm boron.
e - Maximum limits unknown.
f - No measurable amounts found; lower limit of test unknown
g - From Davis and DeWeist (1966, p. 131).
nt- not tested.
x - greater than recommended drinking water limits.
y - 3 x greater than recommended drinking water limits.
z - 10 x greater than recommended drinking water limits.

Table 7. Water quality data for 31 samples.

EXPLANATION FOR TABLE 7

OW-1 Gillette, Wyo. New 850 gpm well 2 miles NNW of Wyodak N. Pit. Used for I-90 construction. Depth about 90', in coal (?). July 22, 1974.

OW-2 Gillette, Wyo. Ground water in open pond in scoria pond 1 mile east of Belle Ayre Mine, AMAX Coal Co. March, 1974.

OW-3 Gillette, Wyo. Stock well at windmill 1 mile N. of Wyodak N. Pit. Shallow well (100' ?) in alluvium, and bedrock (shale, sandstone, and/or clinker (?).July 22, 1974.

OW-4 Gillette, Wyo. Stock well at windmill 1 1/2 miles W. of Wyodak N. Pit, about 1/2 mile N. of Rt. 16. Shallow well (100'?). July 22, 1974.

OW-5 Gillette, Wyo. Domestic well of Dale Mills, 2 miles NNW of Wyodak N. Pit. Shallow well, probably 50' deep in clinker over coal. July 22, 1974.

OW-6 Gillette, Wyo. Seeps from prominent bedding plane in center of 55' cliff of coal on N. side of N. pit at Wyodak. July 23, 1974.

OW-7 Gillette, Wyo. Seeps from SW corner of S. pit at Wyodak. Seep is at contact of 10" clay parting 35' above base at the 85' coal bed at Wyodak. July 23, 1974.

OW-8 Gillette, Wyo. Seep in NW corner of S. pit at Wyodak. Coming from under spoils. July 24, 1974.

OW-9 Sheridan, Wyo. Monarch strip mines, 3 miles N. of Monarch, Wyo. Pond in abandoned strip mine. July 31, 1974.

OW-10 Sheridan, Wyo. Big Horn Mine, S. end of Main pit. Seeps from under active dump. July 31, 1974.

OW-11 Decker, Mont. Decker Coal, SW face of active pit. Seeps from 5' over top of coal. August 1, 1974.

OW-12 Kleenburn, Wyo. Fish ponds in old dumps along Tongue River at Boy Scout park. August 1, 1974.

OW-13 Colstrip, Mont. Rosebud Mine, Western Energy Co. Mont. Bur. Mines Well #S-1, 1/3 mile S. of R. R. loading tipple in 1968 reclaimed spoils. Well depth = 45'. Static = 44'. August 21, 1974.

OW-14 Colstrip, Mont. Rosebud Mine, Western Energy Co. Pond at West end of old 1968 Burlington Spoils. August 21, 1974.

OW-15 Colstrip, Mont. Rosebud Mine, Western Energy Co. Pond in spoils in semi-reclaimed bulldozed spoils. August 21, 1974.

OW-16 Colstrip, Mont. Rosebud Mine, Western Energy Co. Pond in bottom active pit. August 21, 1974.

OW-17 Colstrip, Mont. Rosebud Mine, Western Energy Co. Pond in Pit #3, a deep ground water pit 2/3 mile N. of tipple. Has panfish. Old unreclaimed spoils. August 21, 1974.

OW-18 Colstrip, Mont. Big Sky Mine, Peabody Coal Co. Pond fed by seeps at bottom of pit, coming from ground water in Rosebud coal seam. August 22, 1974.

OW-19 Colstrip, Mont. Big Sky Mine, Peabody Coal Co. Pit in west end, probably ground water recharged. August 22, 1974.

OW-20 Colstrip, Mont. Big Sky Mine, Peabody Coal Co. Pond in spoils 300 yds. NE of S. end of W. highwall. Could be mostly rain runoff. August 22, 1974.

OW-21 Acme, Wyoming. Dug well on N. side of Acme-Kleenburn Road, 200 ft. E. of Tongue River Bridge. Static Level 6 ft. May 20, 1975.

OW-22 Decker, Montana. Windmill 3/4 mile NW of Decker Mine Tipple. June 4, 1975.

OW-23 Monarch, Wyoming. Ground water pond in Welch Mine, 3 miles W. of Monarch. June 5, 1975.

OW-24 Monarch, Wyoming. Pumped well at Hidden Water Creek pump test site 2 1/2 miles NNW of Monarch. 11:17 a.m., June 23, 1975.

OW-25 Monarch, Wyoming. Pumped well at Hidden Water Creek pump test site 11:45 a.m., June 24, 1975.

OW-26 Monarch, Wyoming. Surface pond in spoils area at Hidden Water Creek pump test site. 11:45 a.m., June 24, 1975.

OW-27 Acme, Wyoming. Goose Creek at Bighorn Mine pump test site, 1/2 mile S. of Acme. 10:18 a.m., July 15, 1975.

OW-28 Acme, Wyoming. Pumped well at Bighorn Mine pump test site. 10:18 a. July,15, 1975.

OW-29 Acme, Wyoming. Pumped well at Bighorn Mine pump test site. 6 p.m. July 16, 1975.

OW-30 Decker, Montana. Ground water in "experimental pit" dug in coal bed, 2/3 mile WSW of main office at Decker coal mine. August 9, 1975.

OW-31 Gillette, Wyoming. Ground water in pond in SW corner of active pit of Belle Ayre Mine. May contain some surface water from Little Caballo Creek. August 14, 1975.

OW-32 Gillette, Wyoming. Ground water from pond in active pit of Best Coal Co "Antelope Mine". Same elevation as Antelope Creek 1/2 mile to north. March 4, 1975.

SUBSTANCE	Ho: $U_1 = U_2$			Ho: $U_1 = U_3$					Ho: $U_2 = U_3$		
	t	t.975	ACC. or REJ.	t	t.95	ACC. or REJ.	t.975	ACC. or REJ.	t	t,975	ACC. or REJ.
TOTAL DISSOLVED SOLIDS	2.5	2.07	R	1.23	1.73	A	2.10	A	3.03	2.14	R
TOTAL HARDNESS	3.16	2.07	R	1.09	1.73	A	2.10	A	2.9	2.23	R
pH	1.79	2.07	A	1.88	1.73	R	2.10	A	2.38	2.23	R
ALKALINITY (MET. ORG)	0.82	2.07	A	1.42	1.73	A	2.10	A	1.67	2.23	A
CALCIUM (Ca)	2.49	2.07	R	1.77	1.73	R	2.10	A	4.35	2.23	R
MAGNESIUM (Mg)	3.02	2.07	R	0.59	1.73	A	2.10	A	2.17	2.23	A
SODIUM (Na)	0.32	2.07	A	1.04	1.73	A	2.10	A	1.13	2.23	A
POTASSIUM (K)	0.47	2.07	A	0.47	1.73	A	2.10	A	0.75	2.23	A
IRON (Fe)	1.36	2.07	A	1.18	1.73	A	2.10	A	0.66	2.14	A
MANGANESE (Mn)	1.20	2.07	A	0.7	1.73	A	2.10	A	0.73	2.14	A
CHLORIDE (Cl)	0.5	2.07	A	1.12	1.73	A	2.10	A	0.52	2.14	A
SULFATE (SO_4)	2.15	2.07	R	1.11	1.73	A	2.10	A	3.16	2.14	R
SILICA (SiO_2)	0.35	2.07	A	2.06	1.73	R	2.10	A	3.00	2.14	R
NITRATE (N)	1.11	2.07	A	0.88	1.73	A	2.10	A	0.96	2.14	A
TOTAL PHOSPHATE (PO_4)	0.49	2.07	A	0.37	1.73	A	2.10	A	0.4	2.14	A

Table 8. Summary of statistical tests for water quality.

U_1 = ground water

U_2 = Water from spoils

U_3 = Surface water

	Coefficient of Permeability (K) gpd. ft^2	Coefficient of Storage (S)	Specific Capacity gpm/ft
Tongue R. Ss. (Lowry & Cummings)	5	10^{-5}	0.5
Tongue R. Ss. (Whitcomb & Morris)	3	--	0.3
Spoils: Dragline (Hidden Valley)	450	0.17	1.7
Spoils: Truck (Bighorn)	4	0.23	0.3
Spoils (Van Voast, 1973)	30	--	--
Coal	--	--	1?
Clinker	--	--	20

Table 9. Comparison of Hydraulic properties of surficial aquifers.